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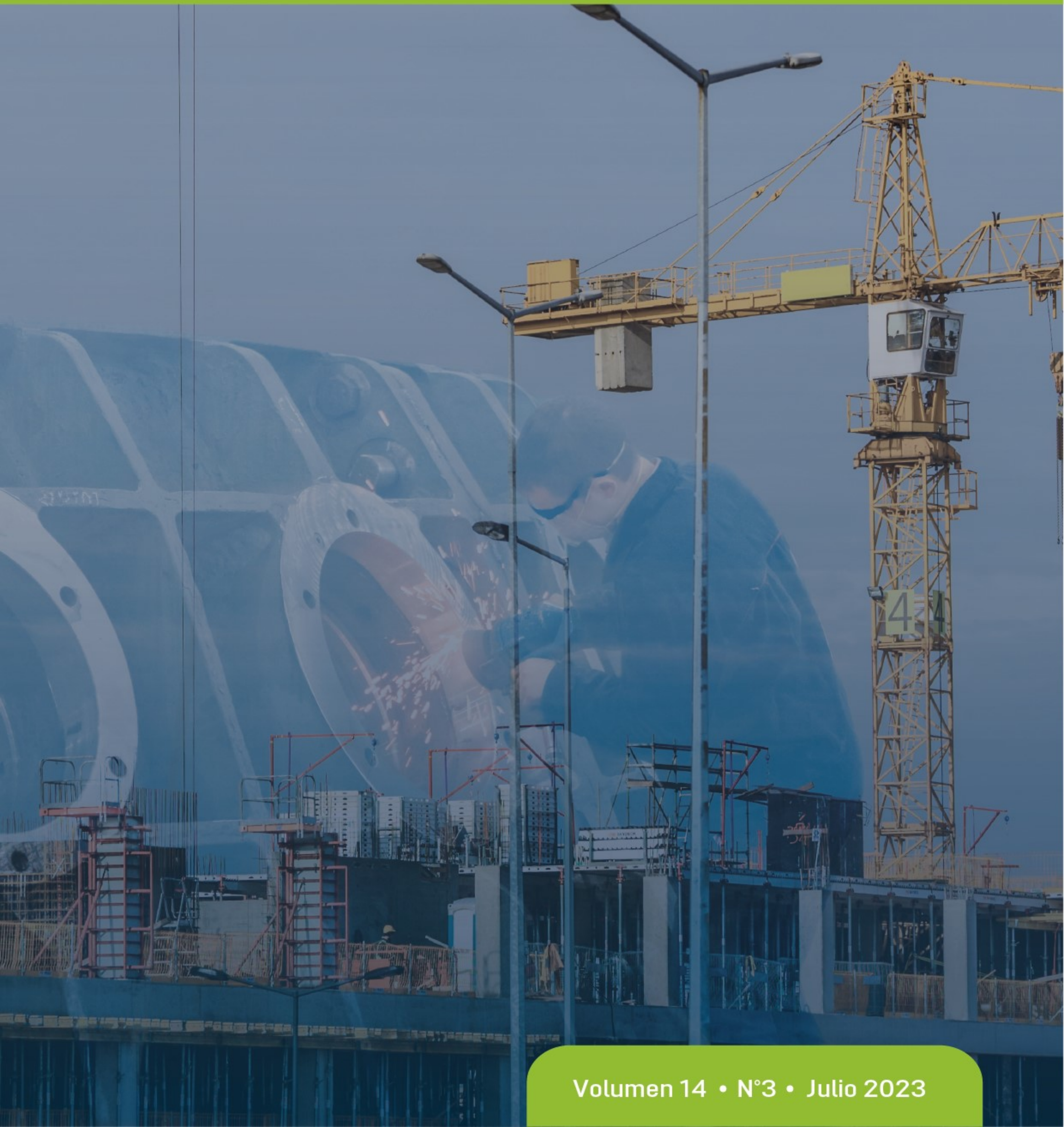

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Sumario

Composting of kitchen waste and pet feces: quality and effect on vegetable germination and growth

Compostaje de residuos de cocina y heces de mascota: calidad y efecto en la germinación y crecimiento de hortalizas

Dalia Carbonel[1] and Tessy Luciano[2]

Abstract **— The rates of urban growth and urbanization indicate a projected increase in waste generation. In developing countries, the organic fraction constitutes approximately half of the total waste, leading to the production of leachate, toxic gases, and the emergence of vectors. Composting emerges as a straightforward and cost-effective solution for organic waste recovery. This study focused on evaluating the quality of compost derived from organic waste (CRO) and pet feces (CM). The research aimed to investigate the impact of these composts on the germination and growth of selected vegetables. The primary quality parameters were assessed, and different mixtures of CRO and CM were implemented as experimental treatments. The majority of the fertilizers examined complied with the quality standards. However, the germination percentage of CRO (18%) and CM (10%) fell below the required threshold (80%), and CM surpassed the recommended maximum level of total coliforms (1100 NMP/g compared to the recommended 1000 NMP/g). Notably, a higher germination percentage (84%) was observed for both CRO and CM at a 25% compost addition. In terms of growth trials, the control group exhibited the tallest plants (13.88 cm), followed by the 10% CRO treatment (13.22 cm) and the 25% CM treatment (11.50 cm). The findings underscore the potential of urban organic waste, including pet waste, for composting and its positive impact on plant growth.**

Keywords **- Capsicum baccatum; compost; organic waste; Raphanus sativus.**

Resumen **— Las tasas de crecimiento y urbanización de las ciudades pronostican el aumento de residuos. En los países en desarrollo la fracción orgánica representa aproximadamente la mitad del total de residuos generados; esta fracción genera lixiviados, gases tóxicos y la aparición de vectores. El compostaje es la alternativa más sencilla y económica para la recuperación de los residuos orgánicos. En este estudio se evaluó la calidad de dos compost elaborados con residuos orgánicos (CRO) y heces de mascota (CM). La pregunta de investigación analizó el efecto de estos abonos en la germinación y crecimiento de hortalizas seleccionadas. Se determinaron los principales parámetros de calidad y se diseñaron tratamientos con diferentes mezclas de CRO y CM. Los abonos evaluados se encuentran en su mayoría dentro de los parámetros de calidad. El porcentaje de germinación del CRO (18 %) y del CM (10 %) fue menor al requerido (80 %); y el CM excedió (1100 NMP/g) el máximo recomendado de coliformes totales (1000 NMP/g). La germinación fue mayor CRO y CM al 25 % (84 % en ambos casos). En los ensayos de crecimiento el control finalizó con mayor altura (13.88 cm), seguido del CRO al 10 % (13.22 cm) y CM al 25 % (11.50cm). Los resultados demuestran el potencial de los residuos orgánicos urbanos, incluyendo los desechos de mascotas, para el compostaje y sus efectos beneficiosos en el crecimiento de las plantas.**

Palabras Clave **- Capsicum baccatum; compost; Raphanus sativus, residuos orgánicos.**

I. INTRODUCCIÓN

La gestión de residuos seguirá siendo un reto, especialmente en ciudades con altas tasas de crecimiento poblacional y urbanización [1]. Se espera que para el 2025 la población mundial ascienda a 8 billones y, en el 2050 a 9.3 mil millones; se estima que de este total el 70 % vivirá en áreas urbanas [2]. Según datos del Banco Mundial [3] en los países en desarrollo la cobertura de recolección fluctúa entre el 50 % y 80 %, los gobiernos locales invierten entre el 20 % y 50 % de sus presupuestos en la gestión de residuos, del cual entre el 80 % y 95 % se destina al transporte y recolección [4]. En gran parte de los países en desarrollo los residuos son dispuestos en rellenos sanitarios, los cuales suelen tener una vida útil proyectada entre 10 y 20 años. Los residuos que no son recolectados, tratados o dispuestos de manera adecuada terminan en botaderos a cielo abierto en las zonas periféricas de la ciudad y contribuyen a problemas de salud pública y riesgos ambientales [1].

Otra característica de los residuos en los países en desarrollo es la composición: a menor nivel de ingresos mayor es la fracción de residuos orgánicos; por ejemplo, en promedio en países de ingresos medios bajos y bajos el porcentaje de orgánicos es de 53 % y 56 %, respectivamente [5]. Cuando estos residuos orgánicos se descomponen, en rellenos sanitarios o botaderos a cielo abierto,

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son los principales responsables de la generación de lixiviados tóxicos, gases metano, contaminación del suelo y acuíferos y la aparición de vectores portadores de enfermedades infecciosas [6].

Entre las opciones de aprovechamiento de residuos orgánicos el compostaje es la más sencilla, económica y utilizada [7]. El compostaje es una tecnología eficaz y rentable y usada ampliamente para el aprovechamiento de gran variedad de residuos orgánicos como estiércol, agrícolas, municipales, etcétera. Así, el compostaje es una alternativa viable y económica para la recuperación de residuos. Entre los residuos orgánicos generados en las ciudades se encuentran también los residuos de mascotas. Dado su alto contenido de patógenos y olores desagradables, el compostaje de este tipo de residuos ha recibido poca atención [8]. La gran mayoría de endoparásitos presentes en las heces de mascotas tienen un ciclo de vida en el que los adultos parásitos tienen una gran capacidad reproductiva; esta carga representa la ruta de exposición más importante de contaminación ambiental y fuente de nuevas infecciones [9]. A pesar de ello todos los residuos orgánicos urbanos tienen gran potencial para ser compostados. Los residuos de animales son ricos en fósforo y nitrógeno [10] y los residuos de cocina en carbohidratos, proteínas, lípidos y ácidos orgánicos [11]; todos estos compuestos beneficiosos para la fertilización de plantas. Sin embargo, el compostaje en zonas urbanas requiere de amplios espacios durante varios meses para posibilitar la degradación completa de la materia orgánica; frente a ello una solución es reducir el tiempo de compostaje para aumentar la capacidad de procesamiento.

En este artículo se presentan los resultados de una investigación que pretende llenar el vacío de conocimiento en términos de composición de residuos orgánicos urbanos, calidad del compost de residuos de mascotas (CM) y calidad de compost de residuos orgánicos (CRO) cosechado en menos de tres meses. Para ello se estudió el efecto de un CM y CRO en la germinación del rabanito (*Raphanus sativus*) y el crecimiento del ají (*Capsicum baccatum*). Este trabajo se realizó tomando como referencia las prácticas de aprovechamiento de residuos orgánicos domiciliarios de Lima Compost.

II. MATERIALES Y MÉTODOS

A. Procedencia y compostaje de residuos orgánicos

Los residuos orgánicos y el compost se obtuvieron de Lima Compost, una empresa dedicada al compostaje de residuos orgánicos y heces de mascotas (perros y gatos); su cobertura abarca 35 distritos de la zona Centro de Lima Metropolitana y sus principales clientes son hogares, restaurantes y negocios. Lima Compost realiza el compostaje en pilas con volteo manual. Para el armado de la pila de compost se coloca una base de materia seca de 25 cm de altura, luego se agrega una capa de residuos orgánicos o de heces de mascotas mezclados con aserrín. Esta primera capa se cubre con hojarasca húmeda proveniente del tamizaje del compost; encima se agregan 20 L de microorganismos benéficos. Estas dos capas se mezclan y se cubren con materia seca. Se repite el proceso hasta llegar a la altura final. El volteo es semanal. El pH, humedad y temperatura se controlan semanalmente, tres veces a la semana y con un equipo multiparámetro de medición directa en el suelo. El CRO se riega entre una a dos veces por semana y se voltea tres veces al mes. El CM se riega y se voltea una vez cada tres meses. El CRO se cosecha luego de diez semanas y el CM después de cinco meses.

B. Composición de residuos orgánicos

Para determinar la composición de los residuos orgánicos se realizó un muestreo tres veces en una semana (martes, jueves y sábado) en dos momentos del año: noviembre y febrero. Cada muestra consistió de cinco baldes (50 kg en total) de residuos sin procesar. La muestra se mezcló para homogenizar y, con el método del cuarteo (fig. 1), se seleccionó una muestra de 10 kg.

Fig. 1. Cuarteo de residuos orgánicos

C. Caracterización de la calidad del compost

Aunque el compost es un abono orgánico de amplio uso y comercialización, no todos los países cuentan con una norma que establezca parámetros mínimos de calidad. En América Latina solamente Argentina, Chile, Colombia y México cuentan con pautas oficiales de calidad del compost. Estos estándares están basados en los de Estados Unidos y la Comisión Europea [12]. Los parámetros de calidad considerados para caracterizar el compost se tomaron de estas normas, resumidas en la tabla 1.

En la tabla 2 se indican los parámetros de calidad evaluados y las metodologías utilizadas.

TABLA I
PRINCIPALES PARÁMETROS DE CALIDAD DEL COMPOST

País	Argentina	Chile	Colombia	México	EEUU	Comisión Europea
Año de emisión	2018	2004	2011	2018	1990	2022
Número	Resolución Conjunta 1/2019	Norma Chilena Oficial Nch2880.Of2004	NTC-5167	NMX-AA-180-SCFI-2018	–	2022/1244/CE
Organización normativa	Servicio Nacional de Sanidad y Calidad Agroalimentaria	Instituto Nacional de Normalización	Instituto Colombiano de Normas Técnicas y Certificación	Dirección General de Normas	*US Composting Council*	Comisión Europea
Olores	No debe presentar olores desagradables	Sin olores desagradables	–	Agradable a tierra húmeda de bosque	–	–
Tamaño de partícula	≤16mm	≤16mm	–	≤30mm	< 76.2mm	–
Humedad	< 60 %	30-45 % BH	20-35 %	40 – 50 %	30-60 %	< 33 (% BS)
CE en dS/m, dilución 1:5	(A/B)* <4/<6	(A/B)* <3/≤8	–	0.5 - 12	<4	–
C/N total	(A/B)* ≤20/≤30	(A/B)* ≤25/≤30	–	15 - 25	–	–
pH	5 – 8.5	5 – 8.5	4-9	6.7 – 8.5	6 – 7.5	–
Materia inerte (impurezas)	Plásticos flexibles o películas, piedras, terrones: de tamaño > a 4mm ≤ a 5 % masa en BS). Vidrio, metales, caucho, plásticos rígidos: de tamaño > a 2mm (≤ 0.5 % masa en BS)	Plásticos flexibles o películas, piedras, terrones: de tamaño > a 4mm (≤ a 5 % masa en BS). Vidrio, metales, caucho, plásticos rígidos: de tamaño > a 2mm (≤0.5 % masa en BS)	Plástico, metal caucho > 2mm: <0.2 % BS. Vidrio > 2mm: <0.02 % BS. Piedras > 5mm: <2 % BS. Vidrio >16mm: no detección	–	Metales + vidrio + plásticos <1 % BS	Vidrio y metales: > a 2mm, tiene que ser ≤ a 0.3 % BS. Plástico: > a 2mm, tiene que ser ≤ a 0.25 % BS. Plástico + Vidrio + metales: > a 2mm, tiene que ser ≤ a 0.5 % BS
Densidad aparente		≤700 kg/m3	0.6 g/cm3	12 - 16 g/cm3	–	–
Materia orgánica	≥ 20 %	≥ 20 %	≥ 15 %	≥ 20 %	> 500 %	≥ 15 %
Contenido de nutrientes	–	≥ 0.5 % N total en BS	>1 % (c/u) de N total, P2O5, Ca, Mg y K	N, P, K (% BS) entre 1–3 % en cualquiera de ellos	N total 1.12 % BS, P_2O_5 0.21 % BS, K_2O_5 0.50 % BS, Ca 3.64 % BS, Mg 0.89 % BS	–
Estabilidad	Grupo 1: <10 g/kg, CSA/N total ≤ 0.7 Grupo 2: Producción de CO_2 < 120mg CO_2/kg.h, Test Solvita ≥ 5 para CO_2, IRE ≤ 0.5 mgO_2/g MO.h, IRD ≤ 1 mgO_2/g MO.h	Grupo 1: Respiración del suelo ≤ a 8 mg de C-CO_2/g de MO/día, Absorción de O_2 ≤ 3.5 mg de O_2/gr MO/día, Autocalentamiento ≤ a 20°C Grupo 2: Relación amonio/nitrato ≤ 3, Concentración de amonio ≤ 500 mg/kg, Contenido de ácidos orgánicos volátiles ≤ 300 mg/kg	–	–	SOUR <3 mg O_2/g MO/d, Tasa de evolución de CO_2 <2 mg CO_2-C/gr MO/d,	Índice respirométrico máximo 15 mmol de O_2/kg de materia orgánica/h Grado Rottegrad mínimo, en su caso IV
Madurez	Amonio <400 mg N-NH4/kg, relación amonio:nitrato (N-NH_4+/N-NO_3) <0.3; Test Solvita ≥ 4 para NH_3	–	–	–	Test de Solvita 7-8 para CO_2, ≥ 4 para NH_3 NH_4 (mg/kg BS) <500; Relación NH4-N:NO_3-N <3. Respiración del suelo ≤ 8	–

Toxicidad	Índice de germinación con dos especies >60 % (rye grass perenne o anual, tomate, rabanito, cebada, trigo, lechuga o berro (*Lepidium sativum*)	Germinación de rabanitos ≥ 80 %	–	Porcentaje de germinación ≥ 80 %	Porcentaje de emergencia, 80 % mínimo Vigor de germinación 80 %	Porcentaje de germinación > 90 %, Porcentaje de crecimiento > 90 %
Presencia de semillas viables de maleza	–	Germinación máxima de 2 propágulos de maleza por l de compost en cámara de crecimiento por 7 días	–	–	–	Semillas viables y germinación (2 semillas por litro)
Límite máximo de metales pesados (mg/kg BS)	(A/B)* As (15/30), Cd (1.5/3), Cr total (100/270), Cu (150/450), Hg (0.7/5), Ni (30/120), Pb (100/150)	(A/B)* As (15/20), Cd (2/8), Cr(120/600), Cu(100/1000), Hg(1/4), Ni(20/80), Pb(100/300), Zn(200/2000)	As (41), Cd (39), Cr (200), Hg (17), Pb (300)	–	As (41), Cd (39), Cr (1200), Cu (1500), Hg (17), Ni (420), Pb (300), Mo (75), Zn (2800), Se (36)	As inorgánico (10), Cd (1), Cr total (100), Cu (200), Hg (0.45), Ni (40), Pb (100), Zn (300)
Requisitos microbiológicos	Coliformes fecales: <1000 NMP/gr BS, Salmonella sp.: <1 NMP/4gr BS Ascaris lumbricoides <1 huevo viable en 4gr BS	Coliformes: < a 1000 NMP, Salmonella: 3 NMP en 4gr BS, huevos de helmintos viables: 1 en 4gr BS	Salmonella: ausente en 25 gr, enterobacterias: < 1000 UFC/gr, ausencia de *Fusarium sp*; *Botrytis sp*; *Rhizoctonia sp*; *Phytophthora sp*. y de nemátodos fitopatógenos	–	Coliformes: < a 1000 NMP, *Salmonella sp.*: 3 NMP en 4gr BS	*Salmonella spp.*: ausencia en 25 gr o 25 ml, *Escherichia coli* o *Enterococcaceae* 1000 UFC en 1g o 1 ml

*: Compost Clase A y Clase B

BS: Base Seca, CE: Conductividad Eléctrica, CSA: Carbono Soluble en Agua, IRE: Índice Respirométrico Estático, IRD: Índice Respirométrico Dinámico, NMP: Número más Probable, MO: Materia Orgánica, SOUR: Tasa de Respiración Específica, UFC: Unidades Formadoras de Colonia.

TABLA II
METODOLOGÍA PARA LA DETERMINACIÓN DE LOS PARÁMETROS DE CALIDAD

Parámetro	Método
pH	Determinación en pasta saturada con potenciometría
Conductividad eléctrica	Medición indirecta del contenido de sales solubles en extracto acuoso de la pasta saturada en relación 1:5
Materia orgánica	Determinación del carbono orgánico con el método de Walkley y Black
Nitrógeno	Método de Kjeldahl
Fósforo	Método del azul de molibdeno
Potasio, calcio, magnesio y sodio	Espectrofotometría de absorción atómica
Carbono orgánico	Método de Walkley y Black
Humedad	Diferencia de peso y gravimetría

D. Efecto del compost en la germinación y crecimiento de plántulas de rabanito

Todos los ensayos se realizaron en la planta de compostaje de Lima Compost. Los ensayos de germinación se utilizaron como indicadores de la madurez y estabilidad del compost. Estos ensayos se ejecutaron con un diseño de cuatro tratamientos y un control (tabla 3). Cada tratamiento tuvo un porcentaje diferente de compost, el resto se completó con el sustrato usado para el control. Cada tratamiento y control tuvo cuatro repeticiones y cada repetición se compuso de cinco unidades. Se usaron bandejas de germinación de 200 celdas y en cada celda se sembraron dos semillas. Los tratamientos, repeticiones y unidades se dispusieron de manera aleatoria en cada bandeja. El control consistió en una mezcla de tierra preparada que contiene musgo, tierra vegetal, tierra de chacra y fertilizantes sintéticos.

TABLA III
TRATAMIENTOS PARA ENSAYOS DE GERMINACIÓN

Tratamiento	Descripción
CRO 100 %	100 % CRO
CRO 75 %	75 % CRO + 25 % tierra preparada
CRO 50 %	50 % CRO + 50 % tierra preparada
CRO 25 %	25 % CRO + 75 % tierra preparada
CM 100 %	100 % CM
CM 75 %	75 % CM + 25 % tierra preparada
CM 50 %	50 % CM + 50 % tierra preparada
CM 25 %	25 % CM + 75 % tierra preparada
Control	100 % tierra preparada

Las semillas se regaron con agua tres veces por semana, no se añadió ningún fertilizante. El ensayo duró catorce días, la germinación y emergencia se registraron cada dos días. La semilla germinada se contabilizó cuando ambos cotiledones estuvieron visibles. Al término del ensayo se tomaron muestras de cada tratamiento para medir la altura de las plántulas (fig. 2).

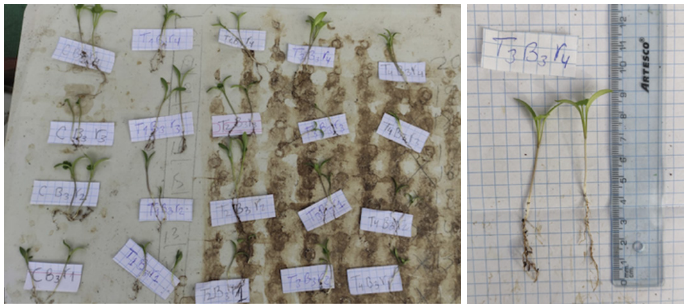


Fig. 2. Muestreo y medición de altura de plántulas de rabanito

Como indicadores de germinación se determinó el porcentaje de germinación (%G), índice de emergencia (IE) [13], germinación relativa (GR) [14], tasa de germinación (TG) [15] y coeficiente de velocidad de germinación (CVG) [16]. A continuación, se describen las ecuaciones usadas para el cálculo de cada indicador.

$$\%G = \left(\frac{Nro\ de\ semillas\ germinadas}{Nro\ total\ de\ semillas}\right) x100\% \quad (1)$$

$$IE = \sum_{i=1}^{n}\left(\frac{PGi}{Ti}\right) \quad (2)$$

$$GR = \left(\frac{Nro\ total\ de\ semillas\ germinadas\ (muestra)}{Nro\ total\ de\ semillas\ germinadas\ (control)}\right) \quad (3)$$

$$TG = \frac{1}{t_{50}} \quad (4)$$

$$CVG = \frac{\sum N_i}{\sum T_i N_i} \quad (5)$$

Donde PGi es el porcentaje de semillas germinadas en el día i, y Ti es el número de días desde la siembra, t50 el tiempo para la germinación del 50 % de semillas y Ni es el número de semillas germinadas.

E. Evaluación del efecto del compost en el crecimiento del ají

Antes de la siembra el ají se germinó en una bandeja y tuvo una frecuencia de riego de tres veces por semana. Luego de la germinación las plántulas se trasplantaron a bolsas de vivero. Se diseñaron tres tratamientos para el CRO y tres para el CM. El compost se mezcló con tierra preparada a diferentes porcentajes; el control consistió solamente de tierra de preparada; los tratamientos se resumen en la tabla 4. Cada tratamiento y control tuvo tres repeticiones y cada repetición se compuso de cuatro unidades. El manejo del cultivo fue a pleno sol, con riego cada dos díasinterdiario y revisiones periódicas para prevenir la aparición de plagas y enfermedades, no se agregó ningún fertilizante. El crecimiento se evaluó durante nueve semanas.

TABLA IV
TRATAMIENTOS PARA ENSAYOS DE CRECIMIENTO DE AJÍ

Tratamiento	Descripción
CRO 40 %	40 % CRO + 60 % tierra preparada
CRO 25 %	25 % CRO + 75 % tierra preparada
CRO 10 %	10 % CRO + 90 % tierra preparada
CM 40 %	40 % CM + 60 % tierra preparada
CM 25 %	25 % CM + 75 % tierra preparada
CM 10 %	10 % CM + 90 % tierra preparada
Control	100 % tierra preparada

F. Análisis estadístico

El análisis estadístico se realizó con el programa SPSS. La diferencia entre tratamientos y semanas se evaluó con la prueba de Anova de un solo factor para un $p<0.05$.

III. RESULTADOS Y DISCUSIÓN

A. Composición de los residuos orgánicos domiciliarios

En la fig. 3 se muestran las fracciones de los residuos orgánicos recolectados por Lima Compost. Los restos de verduras y frutas suman 87 %.

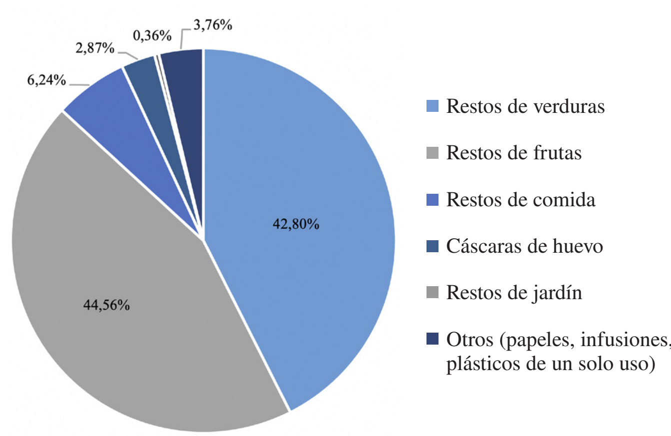


Fig. 3. Composición de residuos orgánicos utilizados para el compostaje

B. Monitoreo del compost

En la fig. 4 se resume el registro de temperatura y pH del CRO y CM. La temperatura del CRO inicia en 60°C, con un descenso progresivo con el paso de los días hasta una temperatura final alrededor de 40°C. El CM inicia alrededor de 30°C, con aumentos y disminuciones durante los días evaluados, terminando en 55°C. El pH del CRO inicia algo más ácido (3.2) que el CM (4); en ambos casos el pH tiene grandes fluctuaciones durante el compostaje, para estabilizarse a un pH neutro de 7.6 al terminar el proceso.

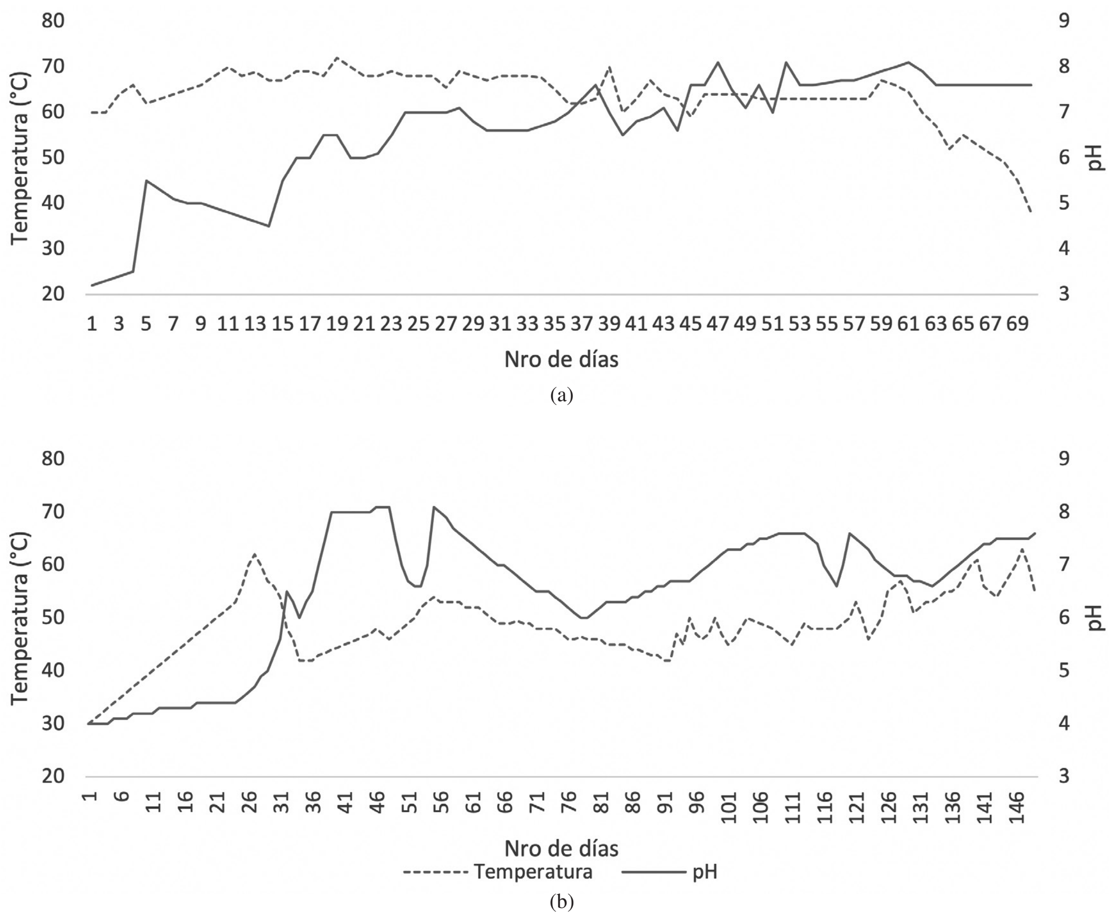


Fig. 4. Monitoreo de la temperatura y pH del CRO (a) y CM (b)

C. Calidad del compost

La tabla 5 detalla los parámetros de calidad del CRO y CM. Ambos abonos cumplen con los parámetros, salvo en el porcentaje de germinación; y, en el caso del CM, este excede ligeramente (1100 NMP/g) el máximo recomendado de coliformes totales (1000 NMP/g). La madurez del compost es un parámetro de calidad relacionado con el crecimiento de las plantas y la estabilidad representa la resistencia adicional a la putrefacción microbiana de la materia orgánica restante [15]. La presencia de compuestos fitotóxicos, bajas dosis de oxígeno o poco nitrógeno disponible en un compost inmaduro o inestable, puede tener efectos perjudiciales para el suelo, la germinación de las semillas y el crecimiento de las plantas [17]. El bajo porcentaje de germinación (18 % para CRO y 10 % para CM) indica que el compost no está maduro y posiblemente contenga compuestos fitotóxicos. A pesar de ello, los resultados de germinación (tabla 6) indican que su uso es seguro a concentraciones menores.

En comparación con el CRO (60.22 %), el CM (38.03 %) tiene menor porcentaje de materia orgánica y ligeramente mayor concentración de metales pesados. La relación C/N es menor en el CM debido a que la materia prima es rica en nitrógeno; sin embargo, ambos valores se encuentran dentro del rango recomendado (12-25 %) para el cultivo de hortalizas [18] y por debajo del rango considerado tóxico para las plantas (30-40 %) [19].

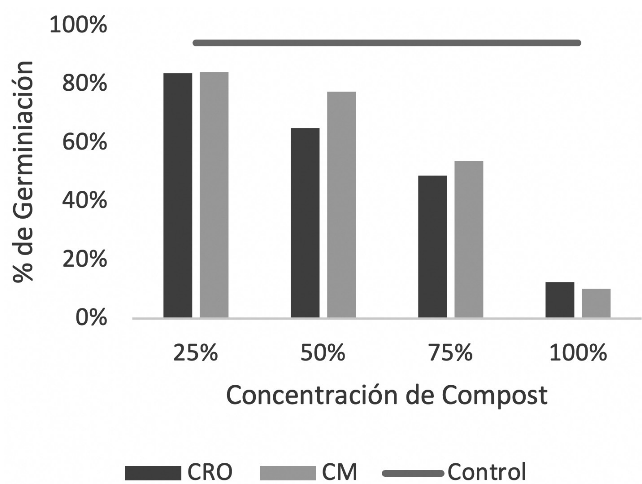
TABLA V
PARÁMETROS DE CALIDAD DEL COMPOST

Parámetros	CRO	CM
Olores	Sin olores desagradables	Sin olores desagradables
Tamaño de partícula	<10mm	<10mm
pH	7.77	6.86
% Materia orgánica	60.22	38.03
C/N total	19.87	11.86
Conductividad eléctrica (dS/m)	5.97	6.08

Madurez		
% de germinación	18 %	10 %
Nutrientes		
% N	1	1.86
% P2O5	0.75	1.89
% K2O	0.67	1.70
% CaO	4.77	7.08
% Na	0.41	0.45
% MgO	0.8	0.96
Metales pesados		
As (mg/g)	4	4
Cd (mg/g)	0.3	0.42
Cr (mg/g)	4	7
Cu (mg/g)	17	29.3
Hg (mg/g)	0.06	0.12
Mo (mg/g)	0.76	–
Ni (mg/g)	2.9	4.5
Pb (mg/g)	5.6	22.3
Se (mg/g)	<1	–
Zn (mg/g)	58	207
Coliformes totales (NMP/g)	460	1100
Coliformes fecales (NMP/g)	–	93
Escherichia coli (NMP/g)	–	9
Salmonella sp. (en 25g)	Ausencia	Ausencia
Huevos de helmintos (en 5g)	Ausencia	–
Enterobacterias UFC/g	440	–

D. Efecto del compost en la germinación y crecimiento de plántulas de rabanito

La tabla 6 y la fig. 5 resumen los resultados del ensayo de germinación. Los datos indican que la germinación de las semillas depende, y está afectada de manera significativa, de la proporción de compost en el sustrato. Se observa que los valores más altos de los indicadores de germinación ocurrieron a una concentración de 25 % de CRO y CM, y fueron mayores para el CRO respecto al CM. Un porcentaje de germinación mayor al 50 % es indicador de un abono adecuado para el cultivo de vegetales [20], siguiendo esta recomendación tanto el CRO como el CM pueden usarse a una concentración del 75 %, aunque la recomendada sería el 25 %. Otros autores [21] encontraron resultados similares al estudiar la germinación del tomate en un compost hecho con residuos de tomate, al aumentar la concentración del compost disminuyó el porcentaje de germinación. Sánchez-Monedero et al. [22] también reportan resultados similares. El porcentaje de germinación más alto ocurrió con el sustrato sin compost. En los resultados se aprecia que el aumento del compost en el medio de germinación redujo la emergencia de semillas y, en consecuencia, disminuyó la tasa de emergencia. Estos resultados pueden tener relación con el pH y conductividad eléctrica del compost. Al aumentar la cantidad de compost en el sustrato aumenta la conductividad eléctrica, lo que reduce la retención de agua [23]. El resultado de estas interacciones es un menor porcentaje de germinación como se encontró en este y en otros estudios [20].



Nota: no se encontró diferencia significativa entre tratamientos ($p < 0.05$)

Fig. 5. Efecto del compost en la germinación del rabanito

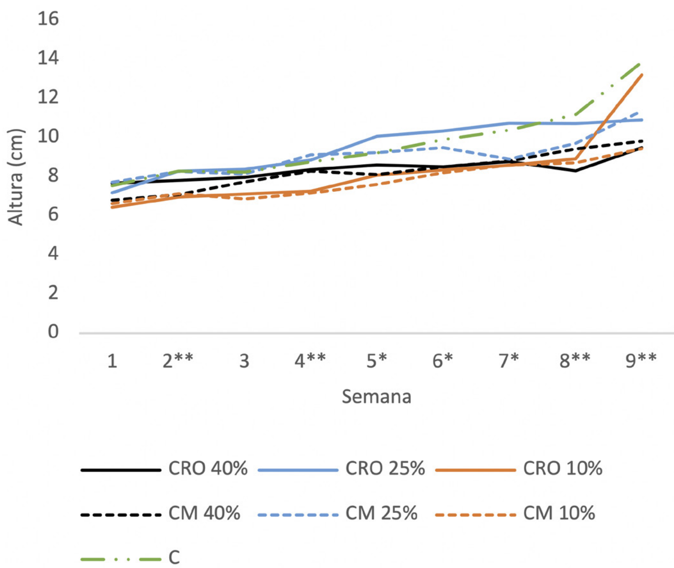
TABLA VI
EFECTO DEL COMPOST EN EL CRECIMIENTO DE PLÁNTULAS DE RABANITO

Indicador	Control	Compost	25 %	50 %	75 %	100 %
IE	0.15**	CRO	0.14**	0.09**	0.06**	0.01**
		CM	0.06**	0.07**	0.04**	0.01**
GR	–	CRO	0.89	0.69	0.52	0.13
		CM	1.02	0.94	0.65	0.12
TG	0.20**	CRO	0.20	0.14	0.14	0.11
		CM	0.14	0.14	0.11	0.09
CVG	15.59**	CRO	15.69**	13.68**	12.70**	10.64**
		CM	12.63**	11.98**	10.22**	9.68**
Altura (cm)	9.9 ± 2.02	CRO	10.7 ± 0.75	6.2 ± 1.85	6.0 ± 1.41	2.5 ± 1.18
		CM	9.1 ± 0.94	9 ± 0.96	7.3 ± 2.30	7.6 ± 1.58

Nota: los asteriscos indican la diferencia significativa entre tratamientos (** $p < 0.01$)

E. Efecto del compost en el crecimiento del ají

En la fig. 6 se observa el efecto de los tratamientos de CRO y CM en el crecimiento del ají. Solamente en la semana uno la diferencia entre los tratamientos no fue significativa, a partir de la semana dos los tratamientos fueron diferentes entre sí. Debido a la condición aún inmadura del CRO y CM el tratamiento con 40 % de compost, en ambos casos, presentaron las menores alturas de crecimiento. El control finalizó con la mayor altura promedio de crecimiento (13.88 cm), seguido de las plantas con CRO al 10% (13.22 cm) y con CM al 25 % (11.50 cm).



Nota: Los asteriscos indican la diferencia significativa entre tratamientos (*p<0.05 y ** p < 0.01)

Fig. 6. Efecto del CRO y CM en el crecimiento del ají

V. CONCLUSIONES

El compostaje es una alternativa económica y sencilla para la recuperación de residuos orgánicos. En este estudio se evaluó la composición de los residuos orgánicos, la calidad del CRO y CM y su efecto en la germinación del rabanito y el crecimiento del ají. La fracción de restos de verduras y frutas representa el 87 % de los residuos orgánicos. Ambos abonos se encuentran dentro de los parámetros de calidad del compost. La excepción es el indicador de toxicidad, el porcentaje de germinación del CRO (18 %) y del CM (10%) no alcanzó el mínimo sugerido (80 %), esto debido al poco tiempo de compostaje; y en el caso del CM excedió ligeramente (1100 NMP/g) el máximo recomendado de coliformes totales (1000 NMP/g). Los ensayos de germinación en rabanito indican una relación inversa entre el porcentaje de compost en el sustrato y el porcentaje de germinación. En los ensayos de crecimiento el control finalizó con la mayor altura (13.88 cm) seguido de los tratamientos de CRO al 10 % (13.22 cm) y CM al 25 % (11.50 cm).

Con base en los resultados obtenidos, se hacen las siguientes recomendaciones para futuras investigaciones. En primer lugar, es importante tener en cuenta que el compost se encuentra en un estado de inmadurez. Por lo tanto, se recomienda realizar análisis físico-químicos de las mezclas seleccionadas de compost para comprender su calidad y comportamiento y optimizar su aplicación en la producción de hortalizas. Asimismo, se resalta la importancia de considerar la variación de los porcentajes de los abonos utilizados para reducir los niveles de pH y conductividad eléctrica. Mantener un pH adecuado y una C.E equilibrada en el suelo es fundamental para garantizar la disponibilidad de nutrientes, fomentar la actividad microbiana beneficiosa, facilitar el transporte de nutrientes, entre otros. Además, se sugiere considerar otros parámetros a medir en futuras investigaciones, como la producción y el tamaño de las hortalizas. Por último, se recomienda realizar análisis microbiológicos de los productos finales para garantizar su inocuidad y calidad fitosanitaria.

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Teaching Industrial Robotics in Higher Education with the Visual-based Android Application Hammer

Enseñanza de robótica industrial en educación superior mediante la aplicación visual para Android Hammer

Alberto Brunete[1,2], Miguel Hernando[1,2], Ernesto Gambao[1,3], Carlos Mateo[2] and Daniel Manzaneque[2]

***Abstract*—Robotics is a demanding subject in higher education. Learning methodologies need to be updated to make use of the new technologies. This paper presents a new methodology for teaching industrial robotics programming using a visual interface running on Android devices, called Hammer. This tool allows the control and programming of robots via a visual environment based on the Scratch concept. Thanks to it, students can see the practical part of theoretical concepts learned in class and, at the same time, test and generate tasks and paths for industrial robots while learning the basics of robot programming. Students don't need to have any knowledge about the target robot programming language, but a basic knowledge of Robotics. This tool has been tested in this paper through four different guided practical exercises. All exercises have been validated through surveys and the results are presented and discussed in the paper.**

***Keywords* - Industrial Robots; Visual programming; HRI; STEM; Android programming.**

***Resumen*—La robótica es una asignatura exigente en la enseñanza superior. Es necesario actualizar las metodologías de aprendizaje para hacer uso de las nuevas tecnologías. Este trabajo presenta una nueva metodología para la enseñanza de la programación de robótica industrial utilizando una interfaz visual que se ejecuta en dispositivos Android, denominada Hammer. Esta herramienta permite controlar y programar robots a través de un entorno visual basado en el concepto Scratch. Gracias a ella, los alumnos pueden ver la parte práctica de los conceptos teóricos aprendidos en clase y, al mismo tiempo, probar y generar tareas y trayectorias para robots industriales mientras aprenden los fundamentos de la programación de robots. Los alumnos no necesitan conocimientos sobre el lenguaje de programación del robot de destino, pero sí conocimientos básicos de Robótica. Esta herramienta se ha probado en este artículo a través de cuatro diferentes ejercicios prácticos guiados. Todos los ejercicios se han validado mediante encuestas y los resultados se presentan y discuten en el artículo.**

***Palabras Clave* - Robots industriales; programación visual; HRI; STEM; programación Android.**

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I. Introduction

NOWADAYS, robots are increasingly present in society, providing the user with a great multitude of applications and utilities, either in professional industry or in daily life. Over the last few years, this has resulted in education emphasizing the teaching of different fields derived from it, such as engineering, mathematics or computing, originating a new teaching methodology named STEM (Science, Technology, Engineering, Mathematics). STEM is based on integrated learning of all scientific disciplines, mainly through problems and open and unstructured situation solving, using the contents and procedures of these disciplines in conjunction.

In addition, the goal of this STEM methodology is that the students work in the classroom in a similar way that an engineer does when facing a problem, promoting the implementation of their knowledge. Furthermore, the reverse process is also achieved, as facing real situations complements theoretical concepts, improves their motivation and broadens the contents of various scientific subjects. This provides the students with a longer learning retention, the ability to transfer among situations and, ultimately, basic learning skills.

Robotics can be effective in teaching STEM [1] [2] because it enables real-world applications of the concepts of engineering and technology. The study by Benitti [3] suggests that educational robotics usually acts as an element that enhances learning (although this is not always the case). Jara et al. demonstrated that robotics subjects are always greatly improved when classroom teaching is supported by adequate laboratory courses and experiments following the "learning by doing" paradigm [4]. Robotics is increasingly being taught in schools, even at earlier stages as suggested by [5], but teachers face a lack of tools to teach it.

Besides, mobile technology (especially combined with tablets and smartphones) provides a new way of using all the utilities that the Internet and computers have in a more versatile way, thanks to all the available sensors and tactile interfaces on them. This way, students can use them and enjoy a much more interactive and effective learning.

In this article, we present a new way of learning the robot basics by mixing the concepts of STEM methodology and mobile applications. The result is an interactive way of learning where the student can manipulate an industrial robot from a tablet and see how the different configurable parameters (speed, type of movement, orientation interpolation, etc.) affect the trajectory created. Therefore, they can program robot tasks with no knowledge about the specific robot programming language, but by applying general robot concepts. Students also have the possibility to see the transcription in the specific robot language once a program has been created.

This is achieved by an application called Hammer, developed at the Universidad Politécnica de Madrid, installable on any tablet running the Android operating system. Hammer allows new users to experience a first contact with industrial robots, which are usually controlled by complex devices that are difficult to use by non-professionals in the sector, this program being the only one available in Android devices that promotes learning of this kind of robot.

The Hammer application is composed of two main components: a teach pendant interface and a visual-programming interface. The first one allows the user to move the robot in different coordinate systems, run simulations of the real robot, create trajectories in a 3D environment and set robot properties such as speed, type of orientation and type of movement. The second component is bound to create a task by using visual programming (drag and drop of blocks in a Scratch way [6]). The user can also run a simulation of the program created to test it before executing it in the target robot. When executing the program in the real robot, the communication between the Android device and the robot is achieved through a gateway, which decodes the instruction into the robot language and executes the task.

Several exercises have been designed to use Hammer as a teaching tool and the first experiences are presented in this paper. In general, we have experienced that students get a better understanding of complex theoretical and abstract concepts with this methodology in an easy and enjoyable way. At the same time, students can achieve simple robot tasks in a very small period of time because the use of Hammer does not require learning the target robot programming language.

The rest of the paper is as follows: section II presents the state of art related to mobile apps for teaching Robotics. Section III describes an overview of the main features of Hammer from the point of view of education. The practical sessions are shown in section IV, and the results and discussion can be found in section V and VI. Finally some conclusions are drawn in section VII.

II. State of the Art

Robotics has a lot of potential in education. The world has an increasing population of robots (e.g. healthcare or agriculture) that need people able to control and program them. End-users could benefit from being able to give robots new tasks [7]. But this is not an easy task. And it is not an easy task to learn.

Mobile applications and visual programming can help with that. Visual-programming software has gained momentum in the last few years because it is an easy and intuitive way to program robots. Although there are not many developments at the moment, we could cite a few. Ruru [8] is a visual language and environment for novice robot programming. Ruru provides a live and concrete environment in which to learn robotic programming. It is live, i.e. its visualisations are animated in real time and can be edited in real time while the robot is operating. It uses visual representations of robot sensors and actuators that the user can interconnect to create behaviours. Visual-programming has also been used with the Sphero robot [9], concluding that "visual programming language (VPL) can also be suitable for robot programming. Furthermore, the main advantages derived from the use of a VPL in such context, when compared to a textual programming language, include a more intuitive and enjoyable programming process, a greater ease of use of the development environment and a better understanding of the tasks to be performed by the robot when viewing the block diagram that specifies a program".

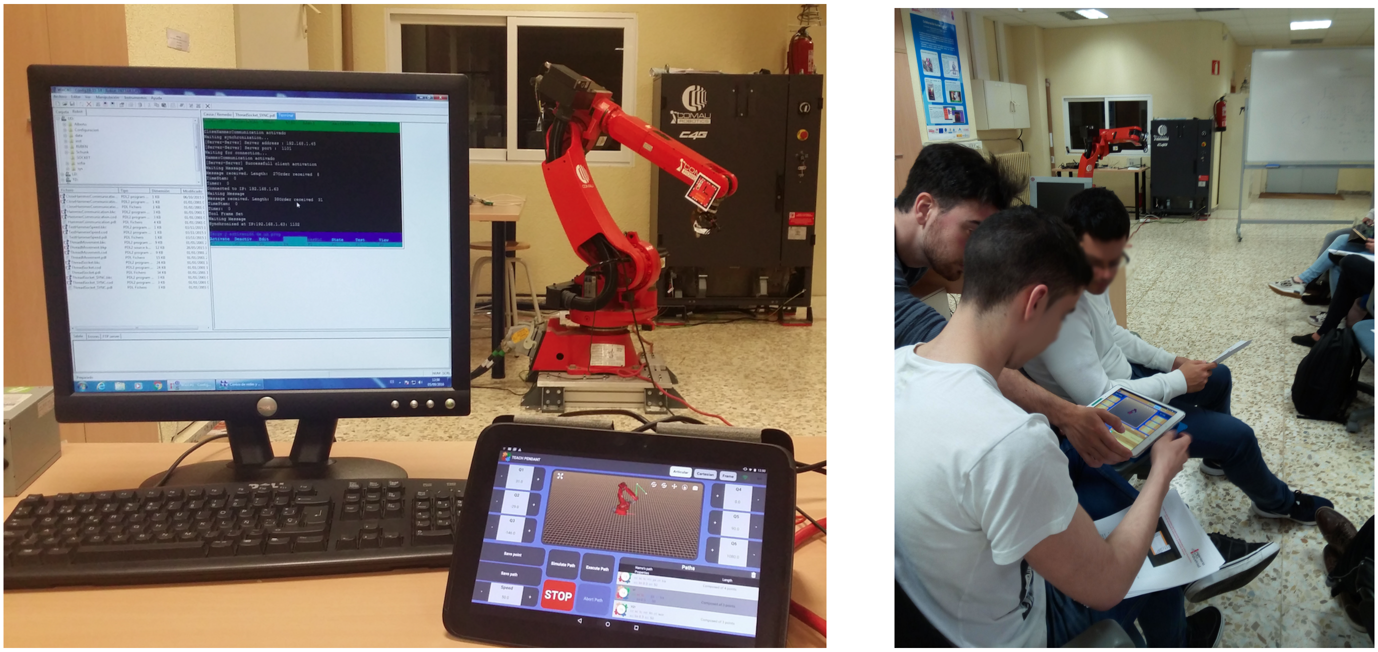
Arts&Bots [10] uses craft materials, a flexible hardware kit, an interactive software environment and adaptable curriculum to empower students to create sculptures with robotic actuation and sensing. The software environment is called "CREATE Lab Visual Programmer", and it is used to perform the storyboarding-step by defining robot behaviours by joining expressions and other program elements into combinations of robot actions that occur over time.

Pichler et al. use augmented reality to facilitate communication and interaction between the operator and robot [7], i.e. by illustrating in a transferred camera image which objects the robot has already detected by itself. The simulator visualises what the robot plans to do, and in this way, the user is also aware of the plans of the robot.

Besides, most smartphone applications related to robotics are primarily focused on mobile robot control. These are applications that remotely control the position of the robot and send the position to the phone [11]. There are applications that report the environmental conditions where the robot is moving, for example, vibrating the smartphone when the robot is close to an obstacle [12]. However, in some cases, the smartphone, due to the large number of sensors it has, is used as a sensing and monitoring unit [13]. It is clear that the main use given to the robotics smartphones applications is for control and monitoring, which allows students to acquire a very basic and simple knowledge about robotics devices.

In the last few years, robot manufacturers have begun to include tactile devices to control their robots, like Universal Robot with its tactile pallette[1], or Comau with its PickAPP application[2], an intuitive interface for robot programming for Android tablets. Educational companies like BQ have developed a browser-based programming environment (Bitbloq[3]) for its

[1] https://www.universal-robots.com/products/ur-robot-benefits/
[2] http://www.comau.com/EN/our-competences/robotics/software/pickapp
[3] http://bitbloq.bq.com



(a) (b)

Fig. 1. Set up for the practical work. (a) System overview. (b) Students during the practical work.

robot Zowi. Modular Robotics has the Cubelets application[4] to control their robots.

The application presented in this paper differs from the aforementioned in that it is used to program real industrial robots, not robots designed for education. It makes use of the potential of tablet devices to control manipulator robots, allowing to create paths, monitor the status of the robot and even create programs and run them both in a simulator and the robot in real time, wirelessly, which is unusual as most of these robots have wired connections.

The idea of programming robots without first having to know about the syntactic and semantic details of the underlying formalism has been previously seen in applications like ReAct! [14], which enables students to describe robots' actions and change in dynamic domains. This concept is developed in the Hammer tool.

III. Hammer Application as a learning tool

Hammer is an Android application designed to control and program industrial manipulator robots [15]. It is able to create and simulate trajectories, manipulate real robots wirelessly and even create generic programs for (theoretically) any kind of robot manipulator, using visual blocks, avoiding the need for specific robot language knowledge. Consequently, users without a specific knowledge in robotics are able to program an industrial robot.

Hammer was originally conceived for industrial applications, but it has turned out to be a great educational robotic tool to show students the operation of industrial robots and basic notions of programming.

[4]https://www.modrobotics.com/cubelets/apps/

The Hammer environment is composed by the industrial robot to control (in these experiments a Comau Smart-Six), the robot controller and a tablet (in our case a Nexus 10 with the Hammer app running). This scenario is shown in Fig. 1 (a). We sometimes use a PC to load programs in the robot, but it is not necessary because the teach pendant can be used instead. The robot must be running a program that acts as a gateway between the robot and tablet. It receives commands from the tablet and translates them into robot-specific language (in this case PDL). Thus, it is possible to use other robots and reuse the application. The only thing that has to be changed is the gateway (to translate commands to the new robot-specific language).

The communication between the tablet and the gateway is done by standard TCP/IP sockets. Thus, WiFi and Ethernet networks can be used.

The application is explained in detail in the paper by Mateo et al. [15]. For educational purposes we use the teach pendant, the programming IDE and the simulator.

The teach pendant interface (shown in Fig. 2) offers a control palette similar to the real device usually found in robotics control units but with an improved, neat and modern interface. Hammer improves the user experience of common teach pendants as it operates wirelessly, allowing the user to walk around the robot and have a clearer view of its position. Furthermore, it has other features such as virtual 3D environment with a model of the real robot synchronized in position and a swipe panel with information about saved points and paths.

This interface allows the user to create points and paths and define the motion properties of them. This is very useful to show students how the robot changes its behaviour depending on the type of point, trajectory and approach. Finally, when

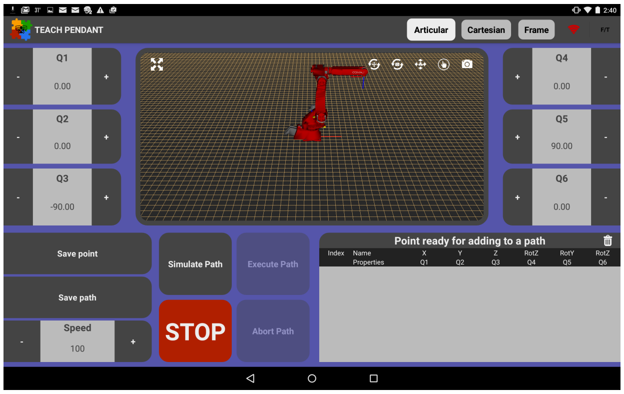


Fig. 2. Teach Pendant screen

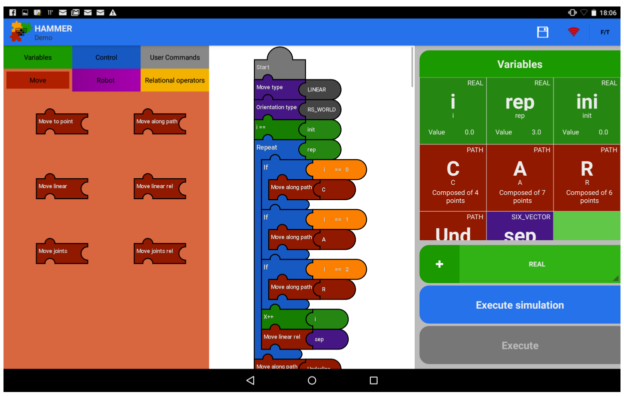


Fig. 3. Programming IDE

the path is generated and configured, the user can simulate it or execute in the real robot.

The programming IDE (shown in Fig. 3) allows the user to make programs that use the saved points and paths to create more complex tasks or routines. To do so, the visual-programming interface provides the user with programming blocks as well as variables, loops and conditionals. The creation of a program is done by sequentially linking one block to another.

Hammer is also able to simulate and execute those programs in the real robot. During the simulation, the user can see the evolution of the program and the variables involved in it, which can be used as debugging tool. When executed in the real robot, the user can see the generated native code by pressing the "PDL" button.

IV. Teaching trials

To validate the usability and improvement on the user experience, we carried out four practical exercises with students. The purpose of these practical exercises was to validate how easy and fast robot programming is done with Hammer.

We selected three groups with between 10 and 15 students from the Escuela Técnica Superior de Ingeniería y Diseño Industrial (ETSIDI) at the Universidad Politécnica de Madrid (UPM) who were following the robotics module of the third year of the Electronics and Industrial Automation grade. Those students had no previous knowledge of the Comau's PDL robot

TABLE I
Square points in the format (x, y, z, roll, pitch, yaw)

Point	Type	Coordinates
1	Joint	50 20 -70 0 93 0
2	Cartesian (Base)	-0.67 -0.77 1.075 -94 91 0
3	Joint	135 13 -102 1 65 86
4	Cartesian (Tool)	0.64 -0.85 0.76 -94 91 0

programming language nor Hammer, although they had some basics in robotics and C programming.

One robot Comau Smart-Six was used for the practical exercises. The students worked in groups, each with an Android tablet. As they finished a task, they connected the tablet to the robot to test their exercise in the robot. Turns were assigned by the instructor. Because it takes more time to write a program than to execute it, this method allows having several students working with the same robot.

Students were given a 20 min tutorial about Hammer. The idea was to check if, with such a short tutorial, they are able to use Hammer. A picture of the class is shown in Fig. 1 (b).

A. Exercise 1: Movement in different coordinate systems and trajectories

The purpose of the first exercise is to teach students the types of movement and how a change in the coordinate reference system affects them.

1) Coordinate systems: The exercise goal is to follow a square trajectory with four points predefined and move the TCP (Tool Center point) from an initial position to the given points: two of them in Joint coordinates, and the other two in Cartesian coordinates (one with respect to robot base, and the other one with respect to the tool). The exercise ends after simulating the trajectory. The coordinates of the four robot locations are shown in Table I.

Students had to place the robot at the targeted positions using the incremental buttons of the teach pendant interface, alternating between the Joint and Cartesian modes, and selecting if the movement has to be done with respect to the robot base or to the tool. When a targeted point was reached, it had to be saved. Finally, with all the points students had to create a path (*exercise1*). Once the path was created, the student had to simulate it to validate and visualize the path. If the simulation was successful, the path was ready to be executed in the real robot.

The purpose of this part of the exercise is to teach students the types of movement that a manipulator robot can do. In this way, students could learn how the robot can be moved and understand better the difference between movement in Joint and Cartesian coordinates.

2) Movement types: When a path is created, the robot arm can reach each of its points by different ways depending on how the movement between points is done. Three interpolation methods have been considered: linear (a straight line in the Cartesian space), circular (the path between two points is an arc) and joint (default joint movement). The idea is that students learn the difference amongst these three movement types.

The goal was to change the trajectory's properties and set the movement type to each of the options available (linear, joint or circular). Then, simulate the movement and finally execute it on the real robot.

B. Exercise 2: Orientation interpolation

The purpose of this exercise is to teach students the importance of tool orientation when designing a robot path, and the difference between three types of interpolation. Students can see how the theoretical interpolation affects the final orientation of the tool, something that could be very practical and clarifying for them.

To reach a target position with a specific orientation, the robot can interpolate the tool's orientation by different ways: world, Euler or wrist joint interpolations (respectively RS_WORLD, EUL_WORLD and WRIST_JNT in Hammer). In world interpolation (two-angles related to the world frame), orientation interpolation is done by linearly interpolating the values of two rotation angles: tool rotation and tool spin. The tool rotation angle is the one created by the common normal between the beginning tool approach vector and the destination approach vector. The tool spin angle is the one created by the approach vector from the beginning position to the destination position. The evolution is related to the World frame independently from the trajectory. In Euler interpolation (Three-angle), orientation interpolation is done by linearly interpolating the values of the three Euler angles of rotation, *E1*, *E2* and *E3*. Finally, in wrist joint interpolation (Wrist-joint), orientation interpolation is done using a combination of joint and linear interpolation. This allows the tool to move along a straight line while the wrist joints are interpolated in joint coordinates.

The starting and ending orientations will be used as taught, but because of the joint interpolation, the orientation during the movement is not predictable, although it is repeatable. For example, using either EUL_WORLD or RS_WORLD, if the beginning and ending orientations are the same, then the orientation of the tool will remain fixed during the motion. However, with WRIS_JNT orientation interpolation, this is not guaranteed. However, WRIST_JNT orientation control produces a smoother motion near wrist singularities.

Therefore, in this exercise, students could experience the difference between the three interpolations described above. To do so, the tool offset must be set to default and the reference system must be set to the base. Then, students had to execute the path *Exercise2* (already created) in the real robot and watch its execution.

The *Exercise2* path was created with a singularity depending on the kind of orientation of the tool. During the execution of the path, students notice that the path execution stops at the middle due to the singularity as during the interpolation TCP tries to reach an orientation whose joints angles are outside the limits of the robot. It happened because the RS_WORLD (World interpolation) property was defined in orientation type. Then, students could try EUL_WORLD (Euler interpolation) and WRIST_JNT (Wrist joint interpolation) and check the difference.

The final result was that in the previous cases (World and Euler interpolation) the interpolation was done using linear spin and rotation angles, which can cause a singularity, whereas the last case, the interpolation (Wrist joint) was done by joint coordinates, which avoid singularities.

C. Exercise 3: Robot speed

The goal of this exercise is to show students how speed can affect the trajectory that the robot should follow.

The process of determining which component governs Cartesian speed is called preplanning. This happens just before the motion actually occurs. It is possible to force the preplanner to pick a particular component of motion selecting one of the options. In the application the user has the following ones available:

- Joint Speed (SPD_JNT): The TCP moves along the requested Cartesian trajectory with maximum speed at (at least) one of its joints. The TCP will not move at constant speed.
- Linear Speed (SPD_LIN): The TCP moves at the specified linear speed value (m/s), forcing all joints to move at the same time.
- Rotational Speed (SPD_ROT): It rotates the TCP at the specified angular speed (rad/s), forcing all other components to move at the same time. For this to be applied, different orientation between consecutive points is necessary.

In this exercise, students should execute a path called *exercise3* with different speeds. First, at the path properties window, the SPD_LIN (Linear speed) option had to be selected and set its value to 0.7 m/s. Students could notice how the robot's TCP moved at the requested speed.

After that, the speed option had to be changed to SPD_ROT (Rotational speed) and set its value to 1.4 rad/s. After that, the path had to be executed to see the difference.

Finally, students had to select the SPD_JNT option. In this case, the speed value is not necessary because the robot moves at least one joint at maximum speed, which means the TCP will not move at constant speed.

D. Exercise 4: Learning visual programming

The purpose of this exercise was to teach students how to make basic programs using the Hammer interface and compare them with the original robot programming language. The exercise was divided into two parts: using motion commands and creating variables and loops.

1) Using motion commands: The purpose of this part was to show students the main usage of movement blocks. Students had to create a program with four trajectories, each of them of a different type: linear movement with respect to the base, linear movement with respect to the current TCP position, joint movement with respect to the zero angle position and joint

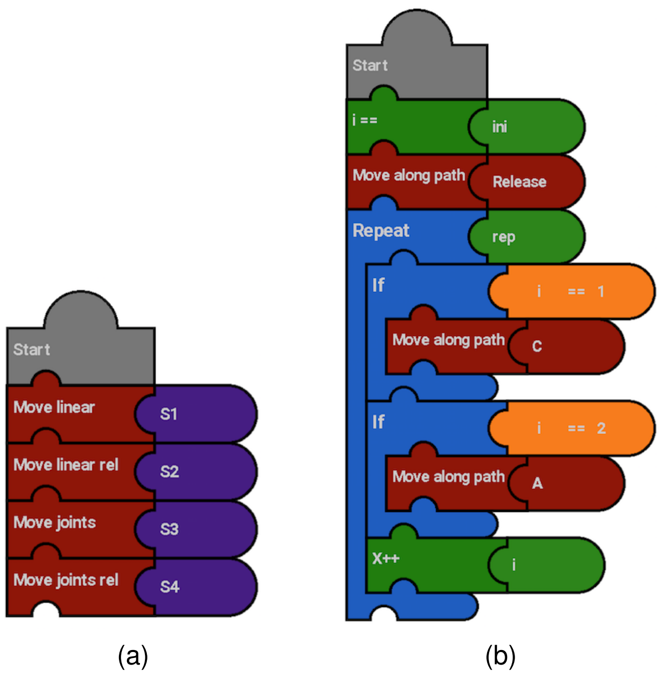


Fig. 4. Program blocks for the practical exercises. (a) Exercise 4.1. (b) Exercise 4.2.

movement with respect to the current joint angle position of the robot. The resulting program had to be the same as the one at Fig. 4 (a).

After that, students can see the equivalent PDL code by pressing the button "To PDL" (Code listing 1). In this way, they could compare the code needed to develop the same program in the robot native language.

Code 1. Equivalent PDL code for Exercise 4

```
hp_properties: HammerPathProperties GLOBAL
auxPathNode: hammerNode
S1, S2, S3, S4: POSITION
BEGIN
  S1:= POS(0.67,-0.77,1.075,-94.0,91.0,0.0)
  S2:= POS(0.1,0.1,0.1,50.0,15.0,12.0)
  S3:= POS(135.0,13.0,-102.0,1.0,65.0,86.0)
  S4:= POS(-45.0,-30.0,40.0,20.0,30.0,40.0)
  MOVE LINEAR TO S1
  MOVE LINEAR RELATIVE VEC(0.1,0.1,0.1) TO S2
  MOVE TO S3
  MOVE BY S4
END HammerProgram_PDL
```

2) Creating variables and loops: In the second part of the exercise, students had to create a more complex program where three paths were combined within conditional and repetition loops (Fig.4 (b)). The aim of this program was to move the robot to an initial position, and then create a loop to execute one path or another depending on the iteration number. This exercise requires the use of different kinds of variables to store values, loops to perform repetition and conditional blocks to switch among paths.

When completed, students should simulate it and execute it in the real robot. Showing the PDL code again made them realize this exercise was harder to develop in the robot native language.

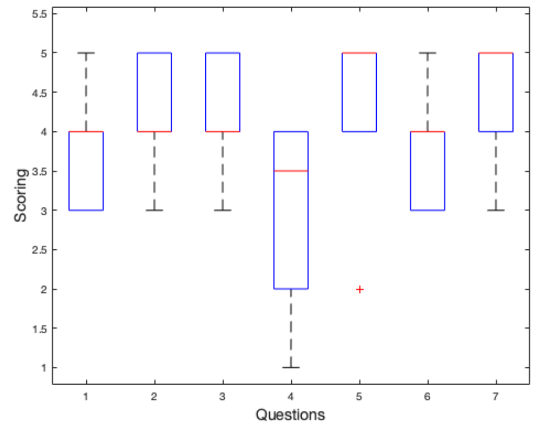


Fig. 5. Scores obtained in the tests.

V. Results

After the practical exercises, students had to answer some questions to evaluate if they think that Hammer has helped them to understand robotics concepts better, such as inverse kinematics, tool orientation, trajectory types and reference systems. All subjects answered to all questions. There was no outlier removal. Questions are presented in the following paragraphs. The scores obtained are summarized in Fig. 5.

1) *Did the practical exercises help to understand the different reference systems applicable to a robot and its usefulness when creating trajectories? (1: Not very, 5: Very much)*
   The answers are shown in Fig. 6a. More than 94% of the students showed that the exercise helped to understand the different reference systems.
2) *Did the practical exercises help to improve the understanding of the theoretical concepts about the inverse kinematics of robots? (1: Not very, 5: Very much).*
   More than 66% of students showed a better understanding of inverse kinematics, as shown in Fig. 6b.
3) *Did the practical exercises help to understand the different types of orientation applicable to the trajectories of a robot and its usefulness? (1: Not very, 5: Very much)*
   The answers are shown in Fig. 6c. More than 83% of the students showed that the exercise helped to understand how orientation affects robot trajectories.
4) *Assess the learning curve of the Hammer tool for the creation and programming of trajectories (1: Easy, 5: Difficult).*
   The answers, shown in Fig. 6d, indicate that the learning curve was somewhat difficult for 50% of the students.
5) *Assess the level of interactivity between the student and the industrial robot through Hammer, that is, how well the robot responded to the user requests (1: Low, 5: High).*
   The answers, shown in Fig. 7a, indicate that more than 94% of the students consider that the interactivity with the robot is increased using Hammer.
6) *Has your interest in programming or robotics increased after the practical exercises?.*

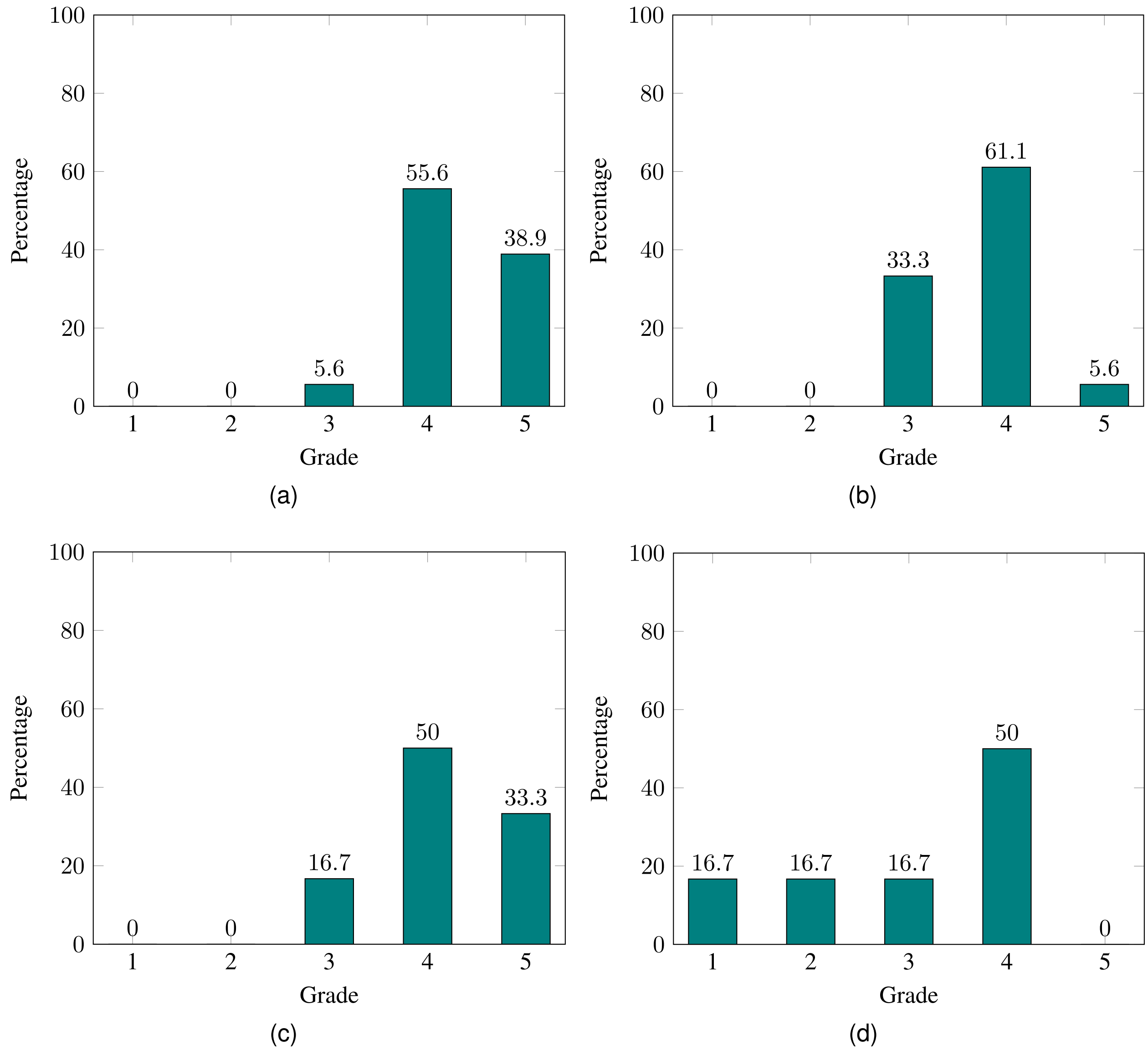


Fig. 6. Survey results for questions one and four. (a) Did the practical exercises help to understand the different reference systems applicable to a robot and its usefulness when creating trajectories?. (b) Did the practical exercises help to improve the understanding of the theoretical concepts about the inverse kinematics of robots?. (c) Did the practical exercises help to understand the different types of orientation applicable to the trajectories of a robot and its usefulness?. (d) Assess the learning curve of the Hammer tool for the creation and programming of trajectories.

The answers, shown in Fig. 7b, reveal that more than 66% of the students consider that their interest in robotics or programming would increase by using a tool like Hammer.

7) *Would you recommend the practical exercises for its realization in future courses?*.
The answers are shown in Fig. 7c. More than 94% would recommend these exercises to prospective students.

Students also had the chance freely to show their opinions about their experience using Hammer. Their comments are summarized in tables II (advantages) and III (disadvantages).

VI. Discussion

As it is shown in the results section, all exercises received a very positive evaluation, obtaining a grade higher that 50% in all cases (considering marks of 4 and 5 points a positive evaluation, 3 points neutral, and 1 and 2 negative). The only question that did not get such a good result was the one about the learning curve. This might be due to the short explanation of the tool (less than half an hour). However, even with such a short tutorial, more than 32% of the students considered the learning curve appropriate. So, the 20 min tutorial seems to be a little short, and we consider too that it would be best to extend it to at least 30 min.

From the student opinions in each group, it can be inferred that most of them have enjoyed the practical exercises and it has helped them to consolidate their knowledge on the subject. According to some students, they assimilated some theoretical concepts that were not understood very well in the theory class. They especially liked the simulation

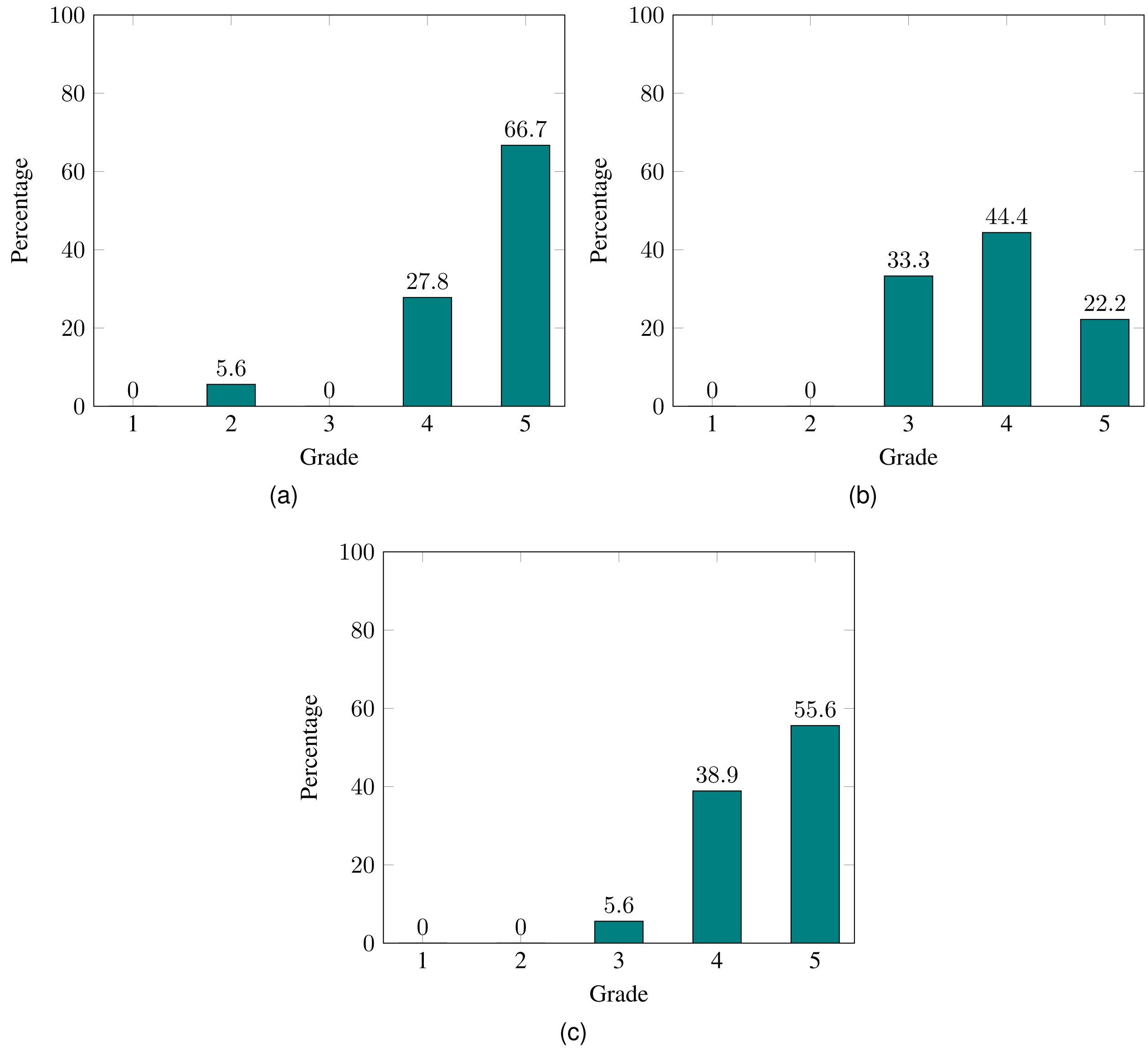


Fig. 7. Survey results for questions five to seven. (a) Assess the level of interactivity between the student and the industrial robot through Hammer, that is, how well the robot responded to the user requests. (b) Has your interest in programming or robotics increased after the practical exercises?. (c) Would you recommend the practical exercises for its realization in future courses?

environment because it allows visualization of the trajectories and corrects them if necessary before the robot executes them. It was also very positive about the translator to native robot code, which could ease the learning curve of the robot native programming language.

Most of the drawbacks were due to lack of tablets and incompatibilities with other operating systems. Hammer is only developed for Android, so students who did not have an Android tablet had to meet with students that did have. This problem could be solved either by increasing the number of tablets or developing Hammer in the future for other operating systems, such as Windows or iOS.

Another point that students missed was the dead man device. Because the control program runs in Hammer over a conventional tablet, it lacked the necessary hardware for its implementation. However, it is not a major drawback as motion range of the robot

TABLE II
COMMENTS FROM STUDENTS: ADVANTAGES

Very intuitive: it was possible to use it without following any tutorial about how it works.
Block interface very useful when the user has no knowledge about robot programming.
Motivation: Allows to see a real and practical application of theoretical concepts learned in class.
A better understanding of robotics concepts like singularities, limits, orientations... As it allows to see the real cases.
The app allows simulating trajectories before executing them, reducing any risk that may be caused in a real environment.
To see the native code of robot programming language within the blocks is amazing, it is a faster way of learning the robot language.
It helps to understand the differences between direct and inverse kinematics as well as coordinate systems types.

TABLE III
COMMENTS FROM STUDENTS: DISADVANTAGES

There were not enough tablets for the practical exercises and we had to work in groups of three students per tablet.
The practical exercises were a bit long. As a result, there was little time left to develop our own programs and execute them in the robot.
The application ran slowly in some tablets.
It would be a good approach to develop the application in other languages such as C++ or support more operating systems such as iOS.
It was difficult to understand the purpose of each exercise because they were too scripted.
Use another type of robot to provide each student with a robot for each student to do the practical exercises individually.

is limited by software to prevent the robot from reaching dangerous positions (such as the ground). For security reasons, Hammer implements a watchdog. If the robot does not communicate with the tablet for the specified time, the robot stops automatically. All in all, students reported a good responsiveness and interaction of Hammer, as shown in Fig. 7.

In general, the criticisms are purely technical and with an easy solution. The general opinion was quite satisfactory and most of the students understood the theoretical aspects covered by the practical exercises, making Hammer a very useful application to teach robotics.

As a summary, we could say that the test was a success. Many students gave a positive review and consolidated their theoretical knowledge in an entertaining and innovative way. We consider that Hammer is a very useful tool to teach robotics to undergraduate students.

VII. CONCLUSION

This paper describes a new teaching method for robotics by which students can use an industrial robot through an Android tablet thanks to the Hammer application developed at Universidad Politécnica de Madrid.

Three groups of 10 to 15 students tested the usability of the application. Each group took part in four different exercises where students could create paths and simulate and execute them on the robot.

The practical exercises were focused on the practical application of the knowledge acquired in theory classes, such as differences between direct and inverse kinematics, types of orientation, singularities and how all these parameters affect the trajectory.

The practical exercises provide students with an introduction to basic concepts of robot programming in an easy and interactive way, as they could create robot tasks using a visual interface and see its subsequent execution in the robot. Furthermore, they could see the equivalent robot code that would have been necessary without Hammer.

VIII. ACKNOWLEDGMENT

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Robotic digital twin as a training platform for rehabilitation health personnel

Gemelo digital robótico como plataforma de formación para personal sanitario de rehabilitación

Sosa-Méndez, D.[1], García-Cena, C.E.[2]

***Abstract*—In the last twenty years, a trend towards the digitization of products and processes has been generated, so the new concept of health 4.0 promotes the use of simulators and digital twins for the training of health personnel, as well as for the personalized planning of patients rehabilitation treatments. This paper presents a virtual training tool for health personnel, which is based on the prototype of a digital twin of an exoskeleton for upper limb rehabilitation. The device was designed in Solidworks® and later its equivalent model was obtained in Matlab/Simulink® software. Through the latter, the functionality of the device is evaluated through the implementation of different therapeutic routines, which help the physiotherapist to plan and evaluate the performance of each patient's treatment. In this case, the evaluation of the movements of the upper limb are generated through independent and combined movements of the shoulder, elbow and wrist joints and, as a result, graphs of the movements are obtained, , as well as a virtual representation of the digital twin and the values of the torques in each joint. Finally, a digital tool that allows the digital twin prototype to be configured to conditions similar to those of the real exoskeleton for automation and supervision tasks is obtained.**

***Keywords* - Digital twin; exoskeleton; Matlab/Simulink®; medical rehabilitation platform; simulation; rehabilitation robotics.**

***Resumen*—En los últimos veinte años se ha generado una tendencia hacia la digitalización de productos y procesos, por lo que el nuevo concepto de salud 4.0 promueve el uso de simuladores y gemelos digitales para la formación del personal sanitario, así como para la planificación personalizada de tratamientos de rehabilitación de pacientes. Este artículo presenta una herramienta virtual de capacitación para el personal de salud, que se basa en el prototipo de un gemelo digital de un exoesqueleto para la rehabilitación del miembro superior. El dispositivo fue diseñado en Solidworks® y posteriormente se obtuvo su modelo equivalente en el software Matlab/Simulink®. Mediante este último se evalúa la funcionalidad del dispositivo a través de la implementación de diferentes rutinas terapéuticas, que ayudan al fisioterapeuta a planificar y evaluar el rendimiento del tratamiento de cada paciente. En este caso, la evaluación de los movimientos del miembro superior se genera a través de movimientos independientes y combinados de las articulaciones del hombro, codo y muñeca; como resultados se obtienen gráficos de los movimientos, una representación virtual del gemelo digital y los valores de los pares en cada articulación. Finalmente, se obtiene una herramienta digital que permite configurar el prototipo de gemelo digital a condiciones similares a las del exoesqueleto real para tareas de automatización y supervisión.**

***Palabras Clave* - Gemelo digital; exoesqueleto; Matlab/Simulink®; plataforma de rehabilitación médica; simulación; robótica de rehabilitación.**

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I. Introduction

Nowadays, digital transformation is imminent, especially in industries where it is mainly sought to increase their productivity and, at the same time, reduces costs through the use of digital representations of their resources; a promising option is through the use of digital twins (DTs) that allow them to exploit them more efficiently, reducing times and avoiding errors, especially in supervision and control tasks. However, a challenge presented by DTs is the ability to model human skills since they are dynamic and changing over time (acquisition of experience over time and adaptable to unforeseen events).

Singh et al in [1] define DT as: "A Digital Twin is a dynamic and self-evolving digital/virtual model or simulation of a real-life subject or object (part, machine, process, human, etc.) representing the exact state of its physical twin at any given point of time via exchanging the real-time data as well as keeping the historical data. It is not just the Digital Twin which mimics its physical twin but any changes in the Digital Twin are mimicked by the physical twin too"; so two types of DT are distinguished, according to their creation time:

1) **Digital Twin Prototype (DTP):** it contains the essential information to create or manufacture a physical copy from a virtual version. It can undergo various test analyses to identify undesirable scenarios before creating its physical twin so the accuracy of the simulation/model determines the quality of the physical twin.
2) **Digital Twin Instance (DTI):** this digital twin is born during the production phase, and is connected to its physical counterpart during its life cycle, which allows the sending of bidirectional data between them; this means any change in one will be reflected in the other.

In the next paragraphs [2], some applicable principles of DTs from different dimensions are summarized:

1) **Product:** applicable to asset-intensive and high-end products with a high single value. Based on the multi-dimensional, multi-time, and multi-scale model.
2) **Complexity:** applicable to complex products, processes and demands. The DT allows its reconstruction, simulation, analysis, verification and performance prediction.
3) **Operating environment:** applicable to extreme operating environments because it supports independent perception of the operating environment, real-time visualization of operating state, multi-scale simulation of multi-granularity and multi-scale, and real-time interaction between virtual and real.
4) **Performance:** applicable to instruments and systems with high precision, high stability and high reliability; it provides real-time performance evaluation, fault prediction, control and optimization decision-making for its installation, commissioning and operation.
5) **Economic performance:** applicable to industries that need to reduce the input-output ratio. It supports information sharing and enterprise collaboration in the industry.

In Zhang, *et. al* [2], four categories of tools and platforms are distinguished: modeling, simulation, operation and interaction, most commercial tools and/or platforms focus on one or a few specific functionalities; those that offer integral functions and strong integration are preferred.

Some of the main areas of application of DTs are:

1) **Manufacturing:** DTs are used in the product engineering process in combination with new technologies, such as: Industry 4.0 [3] and digital manufacturing with Internet of Things [4], achieving technically efficient and economical products for the manufacturer. Some advantages are: 1) they allow manufacturing processes to be automated and 2) they provide early estimates of the product. However, challenges can arise in virtual merging, synchronization, and system integration with multiple DT models.
2) **Logistics and transport:** the use of DT in platforms that control an organization or service is fundamental to improve its efficiency ([5] and [6]).
3) **Electrical energy:** the main goal of energy digital twin technology is to optimize energy efficiency ([7] and [8]). Some challenges present in the data infrastructure are: ensuring the reliability of the sensors, balancing the precision in the simulation and optimization of digital twins, limiting the complexity of the calculation and agglutinating the entire data infrastructure within the feasible investment costs.
4) **Health related:** DTs are applied from concept to practice, as a precision simulation technology, and provide more accurate and faster services for healthcare ([9], [10]). Its challenges are related to the management of personal health throughout the life cycle of patients, and the convergence between the physical world and the virtual world.
5) **Urban management:** the use of DT supports the sustainable design of smart cities ([11], [12]). The main limitations are the lack of fine-grain data, which leads to less accurate simulations.
6) **Agricultural:** DT enables digitalization and provides an approach to overcome current limitations when making decisions and performing their automation ([13], [14]). The challenges they face are due to modeling systems with uncertain factors (human participation).
7) **Automotive:** DTs contribute from the initial stages of design to the use of vehicles ([15], [16]). The challenges they face are due to the technology with which they are developed, big data, and the loss of connectivity in the monitoring of their sensors.
8) **Educational:** DTs is essentially related to industry 4.0, used in learning due to the updating of curricula and the digital transformation of organizations ([17], [18]). The main benefit was the acquisition of experience through its use, and the main barriers were related to the problems of information technologies and the lack of resources.

In the case of the health field, the interactions between patients, medical institutions and insurance organizations are often complex, which makes it difficult to investigate their behavior in real scenarios, which means the use of simulators is a potential field, since their use can help to improve flexibility, reduce medical risks and save costs for medical research; specifically in healthcare, medical surgery training and medical auxiliary equipment design simulation [9].

Therefore, this paper proposes the use of an upper limb robotic exoskeleton through its DTP as a training platform for health personnel focused on rehabilitation. This paper is organized in four sections, as follows: in section 2, a brief literature review of the use of DT as simulation platforms will be disclosed; the development and implementation of the functional performance of the device will be shown in section 3; and, finally, the conclusions and future work in section 4.

II. Digital twin and its applications

An important pillar in all training is the perform of experimental tests for a correct understanding of theoretical notions. However, this requires specific equipment and tools that are usually expensive, which makes the experimental tests limited in number and based on a budget. Nonetheless, there are other options such as the use of virtual technologies that can be applied, such as the flipped classroom, combined experimental teaching and online teaching models [19], which allow the possibility of practicing in simulated environments, giving learners the chance of correcting and repeating experimental tests, helping to improve traditional learning methods.

From a training perspective, the use of DTs allows their implementation in virtual laboratories, promoting continuous learning in an individual, group, organizational and social way, thus designs should focus on users. Berisha-Gawlowski, *et. al* [18] describe the potential of DTs to support human learning and highlights it should be able to work with learning factors, such as autonomy, beliefs, cognitive processes, emotions and social interaction. On the other hand, the duplication of machines and technical systems' DTs will be more accurate if the greatest amount of physical data is available.

In Liljaniemi and Paavilainen [17] the benefits and barriers of DT technology in engineering education were analyzed;

the results showed that students increased their motivation, were self-responsible and improved their learning ([19]). On the other hand, the main barriers are due to the inherent problems of information technologies, lack of resources and inadequate experience of teachers. The introduction of DTs in teaching is due to the updating of curricula, and emerging technologies; for example, for Viola and Chen [20] the concept of intelligent control engineering is introduced, implementing the classic process control through the DTs of a thermal and a mechatronic system.

Madni *et. al* [21] used DTs as key enablers and complements in model-based systems engineering, due to the advantages they present (real-time monitoring, optimization, control, and so on), and analyze their different sophistication levels as well as the integration with systems simulation and the Internet of Things. Five digital technologies are presented by Berisha-Gawlowski, *et. al* [19], including DT and virtual and augmented reality, which were developed for digital pedagogy practices.

In Kaarlela, *et. al* [22], a novel robotic teleoperation platform is presented, compatible with industry 5.0 and based on DTs, which presents functional requirements related to its functionality (teleoperation and robots supervision), and non-functional requirements related to its quality (number of users and availability). Its use allows to reduce inequality, supports remote learning regardless of time and location, which demonstrates its feasibility in online education and training.

The use of DTs is numerous, especially in areas where commissioning can be done through simulated environments. In the case of Engineering, DTs have been used for analysis, monitoring, maintenance, and testing, highlighting the subjects [17] as: control systems ([23], [24]), mechatronics and/or robotics ([25], [26]), sensing ([27], [28]) and vision/artificial intelligence ([29]).

A generic framework for healthcare applications is illustrated in Asad, *et. al* [30], where analysis and forecast data based on DT can help healthcare professionals in their training and improvement of their profession. In the particular case of rehabilitation, Human Digital Twin technology has been accepted, and the concept of Medical Digital Twin (MDT) stands out in areas such as Pulmonology, Orthopedics, and Hepatology. According to the same authors, it is highly useful for the training of users that a DT is centered on the human, and also satisfies the following characteristics: 1) the data from the sensors are direct input, and 2) the sensors have a visual and motion representation for design and validation; in addition to this, in the case of health and well-being, it is highly useful that feedback and interfaces are visual and tactile.

In healthcare in particular, and specially in Medicine, it seeks to provide adaptable therapies to each patient, maximizing their effectiveness and efficiency. To reach this, the optimal therapeutic options require a mechanistic understanding that links genetics and pathophysiology, lifestyle, and the patient's environment. Therefore, the DT is a comprehensive and virtual tool that integrates, coherently and dynamically, clinical data using mechanistic and statistical models [31]; for example, G. Coorey, *et. al* [32] proposed that DTs increase the diagnosis and prognosis of diseases, estimation and stratification of risks, forecast progression, choose intervention and predict its outcome through the transmitted and integrated data. And Hua Huang, et. al, [33] established a DT for personalized healthcare services will be able to incorporate deep learning and machine learning into the data analysis phase; however, its reliability can be compromised if the data sets used do not adequately reflect the environment in which this data must navigate.

According to Elayan, *et. al* [9], the combination of DT and healthcare can be a new and efficient way to provide more accurate and faster services for people's healthcare. Thus, nowadays healthcare simulation research is mainly focused on virtual reality simulation, healthcare mechanical simulation, resource allocation optimization and business process simulation, simulation of clinical trials, and so on. In addition, the Digital Twin Healthcare concept is presented as a new medical simulation approach to provide fast, accurate, and efficient medical services using DT technology with multiscience, multiphysics, and multiscale models.

The creation of DTs can refer to patients (physical characteristics and changes in the environment) and/or medical devices (innovative solutions for the diagnosis and monitoring of treatments) [34]. This means some companies use patient-based simulation models for personalized treatments such as: Sim&Cure, Philips, SIEMENS and Dassault Systèmes, demonstrating its acceptance in the medical field to improve patient care.

III. Methodology and results

In this work, the DTP of an exoskeleton for upper limb rehabilitation is used as a health mechanical simulation tool for the evaluation of movement of the device through the Matlab/Simulink® software. This model allows health personnel to introduce the therapeutic routines that the device must execute to assist the patient, the tests carried out consider conditions close to the real ones such as: anthropometric measurements and patient weight.

The DTP design was made in SolidWorks® for adults (maximum weight 120 kg) with limited mobility in the upper limb; it allows ergonomic adaptation to patients due to its anthropometry (arm (0.40 meters) and forearm (0.39 meters)) and physiology.

The device allows 3 rotational movements for the shoulder (internal/external rotation (q_1), abduction/adduction (q_2) and flexion/extension (q_3)), one rotational movement for the elbow (flexion-extension, q_4) and one for the wrist (abduction/adduction, q_5). In addition to this, it presents a modular design considering mainly additive manufacturing (3D printing).

To evaluate the functional performance of DTP, an equivalent model was obtained in Matlab/Simulink®, which presents 5 degrees of freedom with rotational joints in its entirety, where each complies independently with the movements of the shoulder (S), elbow (E) and wrist (W), respectively. The model obtained is a serial model, and allows adjusting the mechanical properties of the pieces, adjustment of patient weight, and each of the joints allows to adjust parameters such as: internal mechanical (equilibrium position, spring stiffness and damping coefficient), limits (lower and upper), actuation method (torque or motion), sensing (position, speed, acceleration, actuator torque, and lower and upper torque limits), among others. Therefore, it allows independent and combined joints movements, receiving the positions to be reached, as input parameters and evaluating them by means of graphic simulations.

Virtual simulations assume that the patient's arm is attached parallel to the exoskeleton, so the movement executed by the latter will be that performed by the patient's upper limb. The total weight of the DTP is 9.74 kg and considers two types of pieces: a) commercial pieces of carbon fiber and ductile iron, and b) pieces made in 3D printing of acrylonitrile butadiene styrene with 10% fiber carbon. In addition to considering the mechanical properties of the exoskeleton parts, the weight of a patient of 60 kg is also taken into account; which is distributed in the arm and forearm segments with a mass of 1.56 [kg] and 1.38 [kg], respectively. Each rotational joint lacks friction and acts independently through movement, which is indicated through equations (input parameters), and the positions and torques generated in each of the joints are measured at the output (output parameters). The initial position for all movements is when the upper limb is hanging next to the body with the palm of the hand facing inside it and the patient is seated; the simulations show two types of movements executed by the DTP: independent (see Table I) and combined (see Table IV), in each of which the DTP executes two cycles of the input equations expressed in [rad].

In addition to being implemented, the input equations for each movement in the DTP also implemented their first two derivatives respectively; the $q_n^{'}s$ that are not indicated in each movement are equal to zero and the movements are described below:

1) **Shoulder internal-external rotation:** the implemented equation were for q_1 and q_3 (see Table I) therefore q_2=q_4=q_5=0, the resulting motions as well as the virtual DTP can be seen in Figs. 1a and 1b, where joint 1 has a maximum of 0.35 [rad], joint 3 remains constant at 1.57 rad and the rest does not show movement.

2) **Shoulder Abduction-adduction:** the implemented equation was for q_2 (see Table I), therefore q_1=q_3=q_4=q_5=0, the resulting motion as well as virtual DTP can be seen in Figs. 1c and 1d, where joint 2 has a maximum of 1.57 rad and the rest has no movement.

3) **Shoulder flexion-extension:** the implemented equation was for q_3 (see Table I), therefore q_1=q_2=q_4=q_5=0, the resulting motion as well as the virtual DTP can be seen in Figs. 1e and 1f, where joint 3 has a maximum of 1.57 rad and the rest has no movement.

4) **Elbow flexion-extension:** the implemented equation was for q_4 (see Table I), therefore q_1=q_2=q_3=q_5=0, the resulting motion as well as the virtual DTP can be seen in Figs. 1g and 1h, where joint 4 has a maximum of 1.57 rad and the rest has no movement.

5) **Wrist abduction-adduction:** the implemented equation was for q_5 (see Table I), therefore q_1=q_2=q_3=q_4=0, the resulting motion as well as the virtual DTP can be seen in Figs. 1i and 1j, where joint 5 presents a repetitive motion with a maximum value of 0.35 rad and the rest does not present movement.

TABLE I
JOINT EQUATIONS OF INDEPENDENT MOTIONS AT INPUT

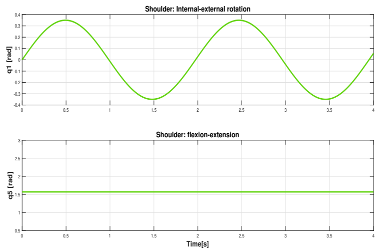
Motion	Joint equations [rad]
S Int-ext rotation	$q_1 = 0.35\sin\left(\frac{10t}{\pi}\right)$
	$q_3 = \frac{\pi}{2}$
S Abd-add	$q_{2_{0-\frac{T}{2}}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q_{2_{\frac{T}{2}-T}} = 0$
S Flex-ext	$q_{3_{0-\frac{T}{2}}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q_{3_{\frac{T}{2}-T}} = 0$
E Flex-ext	$q_{4_{0-\frac{T}{2}}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q_{4_{\frac{T}{2}-T}} = 0$
W Abd-add	$q_5 = 0.35\sin\left(\frac{10t}{\pi}\right)$

The movements described above show independent movements; however, it is possible to perform combined movements in the device through sequences of movements in each of its joints; to exemplify it, the equations of two sequences implemented in the DTP are shown in Table IV. The description of these sequences is reported below (the $q_n^{'}s$ that are not indicated in each movement are equal to zero):

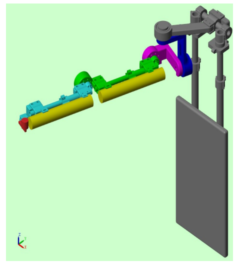
1) **Sequence 1:** the implemented equations were for q_3 and q_4, therefore q_1=q_2=q_5=0 (see Table IV), this sequence executes a shoulder flexion reaching a maximum value equal to 1.57 rad, then it is maintained at the same value during the middle of the cycle while performing an elbow flexion with a maximum value of 1.57 rad; the elbow is held in this position for a $\frac{1}{4}$ of the cycle and then performs an extension with a final value equal to zero. Once the elbow is in this position a shoulder extension with a final value equal to zero is performed (the rest of the joints show no movement). The graphs obtained are shown in Figure 2a and the Figure 2b shows the final position of a cycle of the programmed sequence in the virtual DTP.

2) **Sequence 2:** the equations implemented were for q_1 and q_2, therefore q_3=q_4=q_5=0 (see Table IV), these equations simultaneously execute an abduction (1.57 rad) and an internal rotation (0.52 rad) of the shoulder. The graphs obtained are shown in Figure 2c and Figure 2d present the final position of a cycle of the programmed sequence in the virtual DTP.

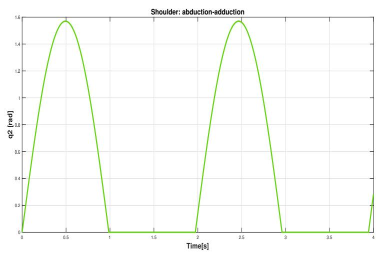
Other parameters obtained in each independent movement with the same conditions were the joint torques generated at the exit of each one; the values of these torques in the maximum positions of each movement are shown in Table II.



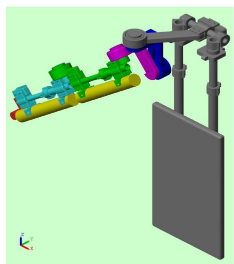
(a) Shoulder internal-external rotation



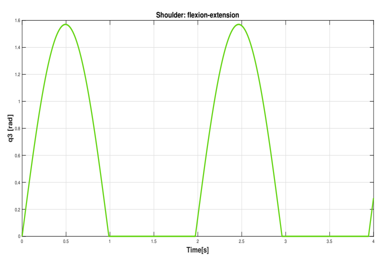
(b) Virtual



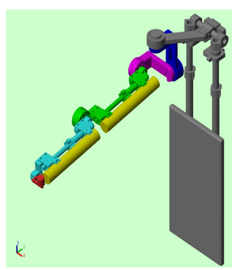
(c) Shoulder abduction-adduction



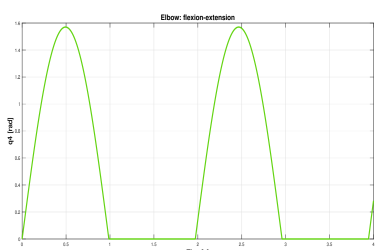
(d) Virtual



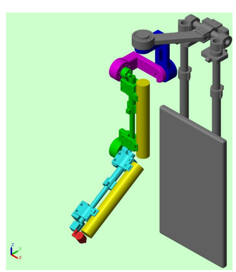
(e) Shoulder flexion-extension



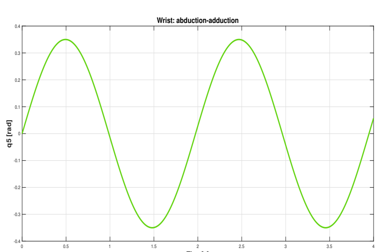
(f) Virtual



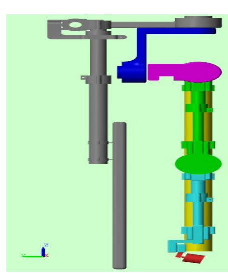
(g) Elbow flexion-extension



(h) Virtual

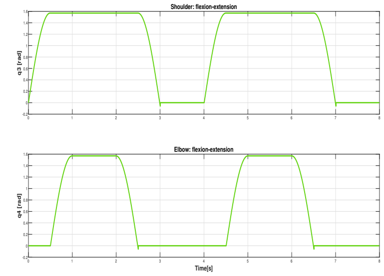


(i) Wrist abduction-adduction

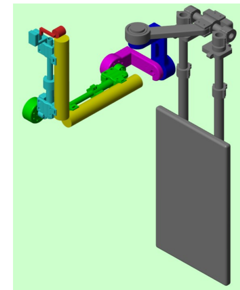


(j) Virtual

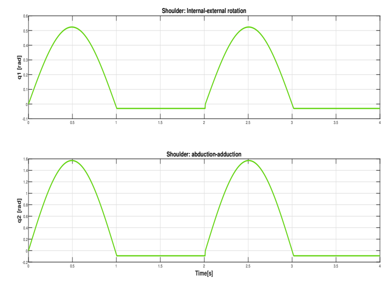
Fig. 1. DTP independent joint movements in Matlab/ Simulink®.



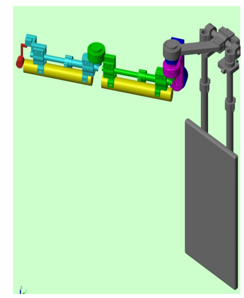
(a) Sequence 1



(b) Virtual



(c) Sequence 2



(d) Virtual

Fig. 2. DTP combined joint movements in Matlab/Simulink®.

TABLE II
JOINT TORQUES OF INDEPENDENT MOVEMENTS AT THE EXIT OF THE DTP

Motion	τ_1 [Nm]	τ_2 [Nm]	τ_3 [Nm]	τ_4 [Nm]	τ_5 [Nm]
S int-ext rotation	-6.87	3.86	23.17	5.38	0.02
S abd-add	0.02	-6.88	-0.01	0.00	0.06
S flex-ext	0.00	3.47	-5.50	3.89	0.06
E flex-ext	0.00	3.85	0.25	-0.19	0.04
W abd-add	0.00	3.85	-0.07	-0.06	0.02

TABLE III
JOINT TORQUES OF COMBINED MOVEMENTS AT THE EXIT OF THE DTP.

Motion	τ_1 [Nm]	τ_2 [Nm]	τ_3 [Nm]	τ_4 [Nm]	τ_5 [Nm]
Sequence 1	0.00	3.85	22.96	9.61	-0.02
Sequence 2	-9.78	-6.99	-9.56	-3.10	-0.02

The torques value obtained in the maximum positions of the combined movements described above are shown in Table III.

In the virtual DTP you can see each device component: base in gray color, link 1 in blue color (it allows shoulder internal-external rotation movement), link 2 in pink color (it allows shoulder abduction-adduction movement), link 3 in green color (allows shoulder flexion-extension movement and its adaptation to the exoskeleton arm segment), link 4 in cyan color (allows elbow flexion-extension movement and its adaptation to the exoskeleton forearm segment), link 5 in red color (allows wrist abduction-adduction movement) and, finally, the patient's arm and forearm are shown in yellow color.

It should be noted that the maximum values of joint torques over time are not the same as those indicated in Tables II and III; this is due to the instantaneous conditions to which the DTP is subjected in each movement. The use of DTP allows to change actuation movements and methods depending on the desired requirements (personalized treatments of patients); it also allows to change the weight of the patient, which makes the simulations and results obtained more realistic. The equations used in this work are only considered to show the performance of each joint through movement, i.e. the implementation of control strategies are not considered in this study.

TABLE IV
JOINT EQUATIONS OF COMBINED MOTION AT INPUT

Motion	Joint equation 1 [rad]	Joint equation 2 [rad]
Sequence 1	$q3_{0-\frac{T}{8}} = 1.57\sin\left(\frac{10t}{\pi}\right)$	$q4_{0-\frac{T}{8}} = 0$
	$q3_{\frac{T}{8}-\frac{2T}{8}} = 1.57$	$q4_{\frac{T}{8}-\frac{2T}{8}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q3_{\frac{2T}{8}-\frac{4T}{8}} = 1.57$	$q4_{\frac{2T}{8}-\frac{4T}{8}} = 1.57$
	$q3_{\frac{4T}{8}-\frac{5T}{8}} = 1.57$	$q4_{\frac{4T}{8}-\frac{5T}{8}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q3_{\frac{5T}{8}-\frac{6T}{8}} = 1.57\sin\left(\frac{10t}{\pi}\right)$	$q4_{\frac{5T}{8}-\frac{6T}{8}} = 0.00$
	$q3_{\frac{6T}{8}-T} = 0.00$	$q4_{\frac{6T}{8}-T} = 0.00$
Sequence 2	$q1_{0-\frac{T}{2}} = 0.52\sin\left(\frac{10t}{\pi}\right)$	$q2_{0-\frac{T}{2}} = 1.57\sin\left(\frac{10t}{\pi}\right)$
	$q1_{\frac{T}{2}-T} = 0.00$	$q2_{\frac{T}{2}-T} = 0.00$

IV. DISCUSSION

The use of robotic devices has shown encouraging and efficient results in clinical rehabilitation treatments [35]. In addition, their interfaces allow to generate personalized therapies in a simple way between patients and medical staff, which makes possible the automation of training routines [36]. A simple and quick way to access this type of device to plan, monitor and automate the main parameters in medical rehabilitation treatments is through its digital twins.

The need to perform personalized and precise rehabilitation therapies, makes it necessary to configure the parameters of the DT to the requirements of the users (anthropometry, physiology and health conditions); therefore, the devices must be functional and efficient for a quick recovery of patients. This, consequently, make medical services also fast [9], [10], [32], [33].

According to the tests carried out in this work: it was demonstrated that the use of joint position variables are a direct way to execute rehabilitation trajectories. Additionally, with the help of the DTP the health personnel can virtually observe the execution of these. The main contribution of this work is to provide the DTP with an upper limb exoskeleton for physical rehabilitation that allows the training of health personnel; therefore, its design was based on the users (physiotherapist and patient) and on the task to be executed (passive rehabilitation), satisfying the characteristics mentioned in Asad, *et. al* [30], Corral-Acero, *et. al* [31] and Zhang, *et. al* [35]. In addition, to minimize the challenges faced by the DTs mentioned in the works of Wagner, *et. al* [3], Bi, *et. al* [4], Yu, *et. al* [7], Teng, *et. al* [8], Liu, *et. al* [9], Elayan, *et. al* [10] and Purcell and Neubauer [14]: the DT developed only contemplates controlling the fundamental parameters of physical rehabilitation, in such a way that the interaction between them and the users is simple, and the date management is only as necessary.

Although most of the DTs implemented in health are focused on the biomechanics of the human being, their models are developed independently (on the one hand, the models of the patients or a part of them, and on the other, the devices); therefore, the interaction between them is achieved through the sensors installed in the devices. In this case, the interaction between the device and the patient is simultaneous through the weight of the latter (variable parameter), which is present during the functional evaluation of the device in a simplified and direct way, without the need for additional sensors, thus representing an advantage of the developed DT.

Although the scope of this work does not address the implementation of DTI, the following safety measures are considered for patient safety, in order of priority: 1) the maximum speeds and displacements that are programmed in the DT depend on the physical rehabilitation treatment defined by the physiotherapist; 2) the joint ranges of motion of the DT are limited to 80% of the workspace considered for a healthy person; and 3) the use of inertial measurement units in the robot to monitor its position during the execution of therapeutic routines is contemplated. For the interaction between the physiotherapist and the device: a graphic interface will be developed, through which the therapist will program the therapeutic routines to subsequently send the control signals to the device.

V. CONCLUSIONS

In general terms, medical health personnel can evaluate the effect of their treatments until they are executed; however, recently, a trend has emerged to use digital tools to evaluate the performance of devices, and have the opportunity to provide feasible and unrestricted training to the personnel who use them: through simulating environments with medical auxiliary equipment and/or patients. An example is the use of DTs that can predict the possible problems that patients may suffer during their treatments before carrying them out, because it allows medical staff to plan and evaluate them before their implementation in patients, reducing risks and saving costs. Some other advantages of DTs are: allows simultaneous use to multiple users, and various tests can be performed due to flexible use and the wide range of approaches that can be implemented; however, one aspect to keep in mind is that medical institutions must have adequate computer resources (trained personnel, equipment, software, simulators and so on). In turn, DTs have the challenge of the high computational work required (high costs to create highly reliable models); nevertheless, it's a tool for human-machine relationships and allow medical personnel to gain experience with the use of cutting-edge technologies in different areas.

This work proposes the use of a DTP as an experimental platform designed for the training of rehabilitation health personnel, focused on a robotic device for upper limb rehabilitation; in the study, the functional performance of the equivalent DTP model was evaluated in Matlab/Simulink ®; the results showed its feasibility in the proposed application, since it allows to reduce costs associated with the acquisition of physical devices in early stages of product development; therefore, there is a tool for carrying out different evaluation and security tests of the device. The implementation of the DT through a graphical interface it's proposed in future works, as well as the perform of various kinematic and dynamic analyses, the develop of control strategies, and the implementation of the DT in pilot tests to health personnel to later evaluate the results obtained in its DTI.

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Pasture potentialities in family farming production systems in Los Ríos province, Ecuador, during the Summer

Potencialidades de los pastos en los sistemas de producción de la agricultura familiar en la provincia de Los Ríos, Ecuador, en el verano

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Abstract **— The aim of this study is to determine the potentialities of the most used grasses in family production systems in Los Ríos province, Ecuador, during the summer. The study was carried out in research areas and in the Ruminology and Nutritional Metabolism Laboratory of the Quevedo State Technical University. The species most used in livestock systems were selected to carry out studies of productive behavior (total biomass, total DMY, leaves and stems) and quality (DM, CP, ashes, OM, P, Ca, NDF, ADF, Lignin, Cel, Hcel, CC, IVDMD, ISDMD, OMD, ME and NLE), which underwent cluster analysis to group species with similarity. For production and chemical composition, three main components were obtained with eigenvalues greater than one and that explain 87.27% of the variability between varieties. In component one, 11 indicators related to protein, energy and the structural components of the cell were shown with values of preponderance greater than 0.75. For the cluster analysis, five groups were formed, with the best results for the third group, made up of *M. maximus* with high values in CP, leaf/stem ratio, ISDMD and ME. All this information would contribute to the design of technological alternatives for sowing, establishment, management, and use of its biomass as a food source where the productivity and sustainability of the ecosystem are minimized.**

Keywords **- chemical composition, conglomerate, pastures, digestibility, energy.**

Resumen **— El objetivo de este estudio es determinar las potencialidades de los pastos más utilizados en los sistemas de producción familiar en la provincia de Los Ríos, Ecuador, durante el verano. El estudio se realizó en áreas de investigación y en el Laboratorio de Ruminología y Metabolismo Nutricional de la Universidad Técnica Estatal de Quevedo. Las especies más utilizadas en los sistemas ganaderos fueron seleccionadas para realizar estudios de comportamiento productivo (biomasa total, RMS total, hojas y tallos) calidad (MS, PB, cenizas, MO, P, Ca, FDN, FDA, LAD, Cel, Hcel, CC, TT, FT, TCT, DIVMS, DISMS, DMO, EM y ENL), a las que se les realizaron análisis de conglomerados para agrupar especies con similitud. Para la producción y composición química se obtuvieron tres componentes principales con valores propios superiores a uno y que explican 87.27 % de la variabilidad entre las variedades. En el componente uno se mostraron 11 indicadores relacionados con proteína, energía y los componentes estructurales de la célula con valores de preponderancia mayor de 0.75. Para el análisis de conglomerados se formaron cinco grupos, con los mejores resultados para el tercer grupo, lo integró el M. maximus con valores altos en la PB, relación hoja/tallo, DISMS y EM. Toda esta información contribuiría al diseño de alternativas tecnológicas para siembra, establecimiento, manejo y uso de su biomasa como fuente de alimento donde se minimiza la productividad y la sostenibilidad del ecosistema.**

Palabras Clave **- composición química, conglomerado, pastos, digestibilidad, energía.**

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I. INTRODUCTION

LIVESTOCK is an activity associated with problems of deforestation, erosion, loss of biodiversity, degradation of pastures and pollution with greenhouse gases (GHG), the latter related also to climate change [1], [2]; the foregoing, coupled with a population demanding food, characterized by a social dichotomy, where the majority of the population in the rural sector is located in the stratum of extreme poverty in contrast to the concentration of wealth in few [3].

On the other hand, livestock systems for ruminants in the world are totally dependent on the availability of natural resources, affected by climate change [4]. This livestock production process generates variation in the availability of forage and, consequently, a reduction in livestock production [5]. These conditions create the need to adopt alternatives, such as implementing sustainable agricultural production systems with environmental conversion to address these problems [6].

However, compared to many other regions of the world, the Latin American and Caribbean (LAC) region is well poised to increase its scale of trade and agricultural production. The sources that give the region a comparative advantage lie, in part, in the abundance of water and land resources. LAC's participation in world agricultural trade went from eight percent in the mid-1990s to 13% in 2015 [7], [8].

The 90% of livestock in Latin America, specifically in Ecuador, is carried out in a traditional way, there aren't livestock and productive records, which prevents proper management of productive and reproductive parameters, which affects profitability. However, due to the great biological richness of the region, there is a great variety of plant species of the tree component that could be managed and used sustainably in animal production systems. Said tree cover could reduce dependence on external inputs (animal feed supplements, fertilizers, herbicides, fossil fuels, and others), in addition to conferring benefits on both animals and producers, due to their multiple uses as fodder, green manure, shade, fences, windbreaks, food, firewood, wood, among others [9].

This approach constitutes an option for the reconversion of traditional agricultural production systems to alternative systems with greater economic and environmental efficiency; it could even contribute to the resilience of landscapes dominated by livestock in the face of the consequences of climate change and the reduction of greenhouse gas emissions[10]; in addition to constitute a viable option for the increase of production in the agricultural systems of Ecuador.

If we take into account the above, the knowledge of the potential of the grass species that best adapt to family livestock systems in Ecuador will contribute to the design of management strategies for these; as well as the proper use and exploitation of the natural resources [11] and of the agricultural or agro-industrial residuals that constitute pollutants [1], which, integrated into the diet of ruminants, become rational elements of nutritional complementation, especially valuable in drought conditions.

Hence, it would be important to know the potential of grasses used in family production systems in Los Ríos province in Ecuador during the summer.

II. METHODS

A. Experimental ecology

The study was carried out in production areas and the Ruminology and Nutritional Metabolism Laboratory of the Quevedo State Technical University, located in the Experimental Campus "La María", km 7 1/2 of the Quevedo-Mocache road, Los Ríos, Ecuador, whose geographical location is 01° 6' and 79° 29' and at 73 meters above sea level (masl). The study of the potentialities of grasses was carried out during the years 2017 and 2018, in the summer period (July-December) for each year.

The climate it is characteristic to the zone called Tropical Monsoon, whose ecological classification corresponds to Tropical Humid Forest [12]. During the experimental period for the years 2017 and 2018, the climatic variables behaved as follows: rainfall of 2,020.6 mm, average, maximum and minimum temperature (25.87, 33.25 and 23.5 °C, respectively) and relative humidity of 90%. For the summer period of both years of study, an average of 202.06 mm of rainfall occurred, 25.32, 33.48 and 23.04 °C of average, maximum and minimum temperatures and 88% relative humidity. The soil present in the area is Dystrandept according to the United States Department of Agriculture, Natural Resources Conservation Service [13] classification and its chemical composition appears in table 1.

TABLE I
SOIL CHARACTERISTICS

Indicator	Value	SD±
pH	5.36	0.03
N, cmolc kg-1	1.48	0.05
P, cmolc kg-1	5.30	0.20
K, cmolc kg-1	0.52	0.01
Ca, cmolc kg-1	1.59	0.05
Mg, cmolc kg-1	0.82	0.05
Sand,%	24.00	2.65
Silt,%	56.00	2.65
Clay,%	20.00	3.46

B. Treatment and experimental design

For the study, a completely randomized block design was used with four replicates and the treatments were the species and varieties (*M. maximus*, *B. dictyoneura*, *B. brizantha*, *B. hibrido* vc Mulato I, *B. mutica*, *Eriochloa polystachya*, *Echynochloa polystachy*a, *A. scoparius*, *C. nlemfuensis*, *Cenchrus purpureus x Cenchrus typhoides*, *C. purpureu*s vc Elephant and *C. purpureus* vc Maralfalfa), which were identified and assorted according to Kröpf and Villasuso's classification [14].

C. Procedures

The areas of each species (4 plots of 25 m², 100 m² in total) had 96% population and at the beginning of the seasonal period (summer) a homogeneity cut was made for the different species and varieties: At a height of 10 cm from the ground, the equalization cut was made for *M. maximus*, *B. dictyoneura*, *B. brizantha*, *B. hybrid* vc Mulato I, *B. mutica*, *Eriochloa polystachya*, *Echynochloa polystachya*, *A. scoparius* and *C. nlemfuensis*; while for *Cenchrus purpureus x Cenchrus typhoides*, *Cenchrus purpureus* vc Elephant and *Cenchrus purpureus* vc Maralfalfa it was 15 cm due to the characteristics that these plants have of using the accumulation of reserve substances in this basal section of the stem in order to produce vigorous regrowth [15].

For the taking of samples, 25 m² plots were delimited; in this procedure, the recommendations of Herrera, Verdecia, and Ramírez [16] for tropical grasses, for the collection of plant material in each plot, 0.5 m, were not taken for each of the edges and the central part was harvested; then, the entire biomass was weighed to determine the yield of total biomass and dry matter (DMY); subsequently, leaves and stems were separated and weighed again to determine dry matter yield of leaves and stems and the leaf/stem ratio. During the experimental stage, irrigation and fertilization were not applied.

D. Chemical analysis

Each species and variety (plots or repetitions, 4 in total, 2 kg of plant material were taken) were deposited in paper bags in cool and shaded places to avoid photorespiration, then they were transferred to the laboratory where they were dried in a forced air circulation oven at 65 °C; later, they were ground to a particle size of 1mm and stored in amber bottles until their analysis in the laboratory in which they were determined: dry matter (DM), crude protein (CP), ash, organic matter (OM), phosphorus (P), calcium (Ca) according to De Lucena, Azevedo, Avelar, Burlamaqui, Nunes, and De Seixas-Santos [17]; neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, cellulose (Cel), hemicellulose (Hcel) and cell content (CC) according to Goering and Van Soest [18].

For in vitro digestibility, the protocol recommended by the manufacturer for the DaisyII® incubator (ANKOM Tecnology, Fairport, NY-USA) was followed, using FN° 57 bags with a pore size of 25 µm and dimensions of 5 x 4 cm made of polyester/polyethylene with filaments extruded in a three-dimensional matrix. In each one, 0.25 g of sample was deposited, to obtain an effective area per bag of 36 cm², which corresponds to a ratio of sample size and bag surface area of 14.4 mg.cm², and they were heat sealed (Ankom Tecnology Corporation).

A replica of each of the species and varieties was randomly incubated in each digestion jar; as well as a bag as a target, in order to generate the correction factor for the possible entry of particles or weight loss. The procedure was performed in duplicate. The samples were incubated for 48 h in the DaisyII® at 39.2 ± 0.5 ºC, with constant shaking and circular movement. After incubation, the bags were washed with cold water to stop the fermentation.

For the *in situ* of dry matter degradability (ISDMD), the method was used [19]. Four Brahman bulls weighing 450.3 ± 35.2 kg-1 and 2 years of age were used, provided with a rumen cannula (4-inch internal diameter, Bar Diamond, Parma, Idaho, USA). The animals were housed in individual pens and fed a diet based on Savoy grass (Megathyrsus maximus), King grass (Cenchrus purpureus) and mulberry (Morus alba), with free access to mineral salts and water. Bags (15 cm x 10 cm) were used for the incubations with a pore size of 45 µm.

Samples for each of the species and varieties were incubated in duplicate in each animal. After 72 hours, the bags were removed, washed with cold water, and frozen at -30 ºC. These were thawed in a refrigerator at 4 ºC, washed with cold water to stop fermentation. The digestibility of organic matter was determined according to Aumont, Caudron, Saminadin, and Xandé [20] and metabolizable energy (ME) and net lactation energy (NLE) were determined according to Caceres and Gonzalez [21]. All analyzes were performed in duplicate and by replicate.

E. Statistical analysis and calculations

For the analysis of the results, the main components were performed, for which the rotation method was applied: Varimax normalization with Kaiser and the Bartlett's sphericity test was performed, which was highly significant ($P < 0.01$) and the KMO statistic (Kaiser -Meyer-Olkin) with a value of 0.60. The reliability of the survey was determined by using Cronbach's Alpha Coefficient with a value of 0.82.

The components were chosen with an accumulated explained variability equal to or greater than 77% and within each factor or main component, those indicators with factors of weight or preponderance greater than or equal to 0.75. With the selected variables, they were grouped and a cluster [22]; analysis was carried out to establish the groups with similarity in their productive components and chemical composition.

For the analysis of principal components, the establishment of the indicators and contribution to explain the variability's between the species and varieties of grasses. It was based on the principle that the relationship between the variables evaluated, a necessary condition to carry out the principal component analysis (PCA), presented correlation values greater than 0.50, with both positive and negative relationships, and that their value was not less than 50% of the total number of these, as well as the non-autocorrelation between variables.

III. RESULTS AND DISCUSSION

For the yield and chemical composition in summer, three main components with eigenvalues greater than one were obtained and that explain 87.27% of the variability between varieties. In component one, 11 indicators related to the constituents of the cell content were shown with preponderance values greater than 0.75 related to the constituents of the cell wall. In the second component, only calcium and the leaf/stem ratio were determined, and in the third component, biomass and dry matter yield (table II).

The first component shows that these indicators explain the greatest variability (62.77) and showed NDF, ADF, Cel, Hcel, ratios of neutral detergent fiber/nitrogen (NDF/N) and acid detergent fiber/nitrogen (ADF/N) as those of greater effect on the quality of grasses. This may be due to the type of growth that these species present and to the decrease in the crude protein content and the increase in the cell wall with the maturity of the plant [23]; aspects that were demonstrated in the current investigation, although in the case of grass species the fibrous content is more marked than in other forage species.

TABLE II
MAIN COMPONENTS OF THE PRODUCTION AND COMPOSITION OF GRASSES IN SUMMER

	Components		
	Cell content	**Minerals and leaf/stem ratio**	**Yield**
Total biomass	0.114	0.398	0.769
Total DMY	0.195	0.401	0.782
DM	0.827	-0.402	0.053
CP	-0.926	-0.065	0.179
Ca	0.251	0.850	-0.255
P	0.624	0.058	-0.107
NDF	0.964	0.028	-0.171
ADF	0.984	0.082	0.011
Lignin	0.915	0.233	-0.098
Cel	0.973	0.048	-0.071
Hcel	0.944	0.166	-0.066
Ash	0.391	-0.504	0.325
ISDMD	-0.795	0.542	0.012
leaf/stem	0.188	-0.850	0.195
AFD/N	0.981	0.138	-0.032
NFD/N	0.971	0.099	-0.163
ME	-0.807	0.532	0.188
Eigenvalue (λ)	10.671	2.885	1.281
Variance (%)	62.769	16.972	7.533
Cumulative variance (%)	62.769	79.741	87.273

In component two, calcium was characterized, and the leaf/stem ratio showed influence in this component and in the third component the day matter yield and biomass. In studies by Cedeno-Vilamar, Arturo, Murilo, and Medina-Vergara [24], and Espinales-Suarez, Pincay-Ganchozo, and Luna-Murilo [26], in the morphobotanical characterization of 19 accessions of *Brachiaria brizantha* and 25 of *Cenchrus purpureus* (Schumach.) vc Morrone, obtained variability in the first component of 24.01 and 24.63, the rest of the components were located in descending order.

This behavior was attributed to the fact that these accessions and varieties belong to the same species and, therefore, have interspecific characteristics that can be very similar and not very variable for some of the indicators in particular, which allows these high productions of biomass, proportion of leaves, rusticity and plasticity; therefore, they adapt to a great diversity of soil types (including those of low fertility) and to adverse climatic conditions (high temperatures and low rainfall) [25]. The differences with our study are related to the differences found between species and varieties with different types of growth, development, phenology, rusticity, and yields; hence the variability's found.

In this sense, when evaluating varieties of *Cenchrus ciliaris* [27], morphologically and nutritionally, they obtained five components with 93% of explained variance, but in the first two the indicators with the greatest preponderance were grouped and 70% of the variability was explained. Where the height of the plant, CP, ADF, lignin, yield in total dry matter and stems stood out in (principal components) PC1 in terms of their preponderance; while PC2 the DMY of the leaves, leaf/stem ratio and IVDMD. These results are lower than those achieved in our research by the different types of species and varieties with different morphology and type of growth. Aspects previously described that reaffirm the variability found since the fibrous structural components in the forages explain the variability in their quality. This agrees with what is written in the literature in relation to the fact that crude fiber determines a minimum of digestible fractions, with a wide range of variability; while the determination of the cell wall offers a more accurate criterion regarding the nutritional quality of the forages (hemicellulose, cellulose and lignin) and the ADF corresponds to the presence of cellulose and lignin.

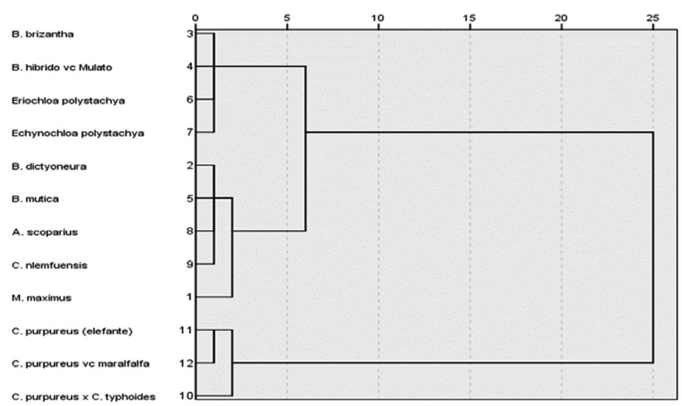

Fig. 1. Dendrogram of the production and chemical composition of the grasses during the summer

The cluster analysis for the main variables allowed grouping according to the similarity in the productivity and chemical composition of the species and varieties during the summer in five groups (fig. 1, table III). The first was characterized by low contents of NDF, ADF, Lignin, Cel, Hcel, NDFN, ADF/N and high CP, ISDMD and ME for the varieties *B. brizantha*, *B. hybrid* vc Mulato I, *Eriochloa polystachya* and *Echynochloa polystachya*, with contributions of nutrients per hectare with 111.51 kg.ha-1 of CP, 710.52 GJ.ha-1 of ME and 397 GJ.ha-1 of NLE.

B. dictyoneura, *C. nlemfuensis*, *A. scoparius* and *B. Mutica* formed the second group with low biomass and dry matter yields. The third group was made up of *M. maximus* with medium to high values in CP, leaf/stem ratio, ISDMD, ME, and variables in the rest of the indicators. The fourth group consisted of *C. purpureus* with the Maralfalfa and Elephant varieties with the highest yields (total biomass and DMY).

C. purpureus x *C. typhoides* integrated the fifth group typified by low levels of CP, ISDMD, leaf/stem ratio, ME, and elevated DM, NDF, ADF, lignin, Cel, Hcel, NDF/N and ADF/N ratios. Where it is the second group showed the lowest contribution of nutrients with 63.2 kg.ha-1 of CP, 490.62 GJ.ha-1 of ME, 256.78 GJ.ha-1; the third, although it presented the best relationship in terms of nutritional contribution (131.58 Kg.ha-1 of CP; 897.28 GJ.ha-1 of ME; 496.64 GJ.ha-1), its contribution was lower than the Cenchrus of groups IV and V with 2242.91 and 1489.15 Kg.ha-1; 18078.12 and 13083.98 GJ.ha-1; 9937.68 and 7045.22 GJ.ha-1 due to differences in productivity.

These results coincide with those reported by De Lucena, Azevedo, Avelar, Burlamaqui, Nunes, and De Seixas-Santos [17], and De Lucena, Azevedo-Rodrigues, Avelar-Magalhães, Burlamaqui-Bendahan, Numes-Rodrigues, and De Seixas-Santos [28], who reported for *B. humidicola* cv. Llanero and *B. brizantha* cv. Piatã protein levels of 10 and 13% and low levels of cell wall, with negative relationships with age. This behavior is attributable to the variety, effect of dilution of nutrients by moisture content, growth and therefore increase of the cell wall and its components; as well as yield, aspects verified in the current investigation due to the variability between varieties due to the type of growth.

In Ecuador, several cultivars of *Brachiaria spp*. have been introduced, which have the potential to increase the productivity of existing grass systems. Among them are Decumbens, Brizantha and Mulato I, of which there are some reports on their acceptance by farmers due to their high nutritional value, adaptation to a wide range of soils and tolerance of pests and diseases [29]. In the current study it was possible to verify that it was present in close to more than 30% of the cattle farms in the study region.

In this sense, Reyes, Mendez, Luna, Verdecia, Macias, and Herrera [30], and Reyes, Mendez, Verdecia, Luna, Rivero, and Herrera [31] found in edaphoclimatic conditions in the regions of El Empalme (Guayas province) (245.6 mm, 25.8 °C, 86% RH) reported for these varieties CP (11.25-12.5%), NDF (37-37.5%), ADF (19.5-21.5%), Lignin (3-3.55%), Cel (17-18%), Hcel (16-16.2%), NDF/N (23-21.37), ADF/N (12.5-12.36), IVDMD (53-53.5%) and ME (7.75-7.94 MJ.kg-1). These results confirm the wide range of adaptation to different climate and soil conditions, which allow the effects of the climatic zone to diminish.

Similar results were reported by Garcia, Pezzani, Lezama, and Paruelo [23], and Bravo, Garcia, Contreras, Pena, Alcala, and de Ortega [32] in *E. polystachy*a and *P. dilatatum*, with values of 12% PB and 38% CP. Meanwhile, Aumont, Caudron, Saminadin, and Xande [20], in *S. splendida* under conditions of the Ecuadorian Amazon, found 11, 77, 35, 39 and 43% of CP, NDF, ADF, Hcel and DMD; respectively. Differences found are due to the type of species and the experimental conditions, since the chemical characteristics are influenced by the degree of maturity of the species, growth and development achieved.

TABLE III
GROUPS OBTAINED IN THE CONGLOMERATE ANALYSIS FOR THE PRODUCTION AND CHEMICAL COMPOSITION OF THE GRASSES DURING THE SUMMER

Indicators	**Group**				
	B. brizantha ***B. hibrido vc Mulato I*** ***E. polystachya*** ***E. polystachya***	***B. dictyoneura*** ***C. nlemfuensis*** ***A. scoparius*** ***B. mutica***	***M. maximus***	***C. purpureus vc Elefante*** ***C. purpureus vc Maralfalfa***	***C. purpureus x C. typhoides***
Biomass $t.ha^{-1}$	2.29±1.52	1.59±0.44	2.48	61.3±3.30	52.72
DMY $t.ha^{-1}$	0.93±0.53	0.74±0.20	1.28	26.43±2.23	20.54
MD.%	28.67±3.89	33.58±1.93	30.27	34.04±0.28	35.59
CP.%	11.19±0.83	8.54±0.77	10.28	8.49±0.44	7.25
Ca.%	0.5±0.15	0.55±0.14	0.52	0.59±0.028	0.64
NDF.%	37.94±4.19	60.21±4.89	52.27	59.9±2.85	68.71
ADF.%	20.85±3.04	36.7±3.74	27.91	41.5±1.07	44.54
Lignin.%	2.79±0.31	4.64±0.76	3.54	4.94±0.16	5.57
Cel.%	16.82±1.41	30.6±1.83	25.84	32.46±1.27	36.24
Hcel.%	16.12±0.57	28.61±2.92	24.4	31.39±1.45	33.35
ISDMD.%	55.33±6.42	47.82±2.41	52.39	48.54±1.26	46.56
leaf/stem	0.79±0.15	0.81±0.092	0.87	0.79±0.013	0.79
ADF/N	11.78±2.41	26.98±2.78	16.97	30.63±2.36	38.41
FND/N	21.4±3.65	44.24±3.63	31.79	44.25±4.37	59.26
EM. $MJ.Kg^{-1}$	7.64±0.70	6.43±0.24	7.01	6.84±0.22	6.37

When evaluating quality indicators, Reyes, Mendez, Luna, Verdecia, Macias, and Herrera [30], and Reyes, Mendez, Verdecia, Luna, Rivero, and Herrera [31] reported interactions between variety-regrowth age (maturity), they concluded that this effect is an indication that these factors should be evaluated as a system and not in isolation, mainly because the climate, soil, its fertility and management; among other aspects, they influence their behavior. These introduced grass species have, as main characteristics, the improvement of the productivity and nutritional value of the pasture with a view to achieving better productive performance (meat and milk) in cattle.

It is interesting that, during the study, higher amounts of leaves were obtained with respect to the stems (leaf/stem ratio) with productivity greater than 50% for this first fraction. However, it maintains the same response reported in the literature for tropical grasses with an increase in NDF/N and ADF/N ratios, as well as a decrease in energy intake (ME; NLE) and digestibility (DMD; OMD) [33].

The decrease in the digestibility of the dry matter is affected by the growth of the plant (maturity). This brings with it a thickening of the cell wall, which reduces the intercellular space where the nutrients (protein) are found and is a function of the relative proportion of each chemical component and its individual digestibility. In addition, it is influenced by the increase in structural components, as well as silica and the monomeric components of lignin. Results higher than 50% digestibility for these species were obtained by [34], [35]. While [33] in *Brachiaria humidicola* cv. Chetumal with cutting frequencies every 21 and 28 days found results of 54-60%; these values are below those reached in the present study, differences attributable to the intrinsic characteristics of each individual, forage age and management conditions.

B. dictyoneura, *C. nlemfuensis*, *A. scoparius* and *B. mutica* formed the second group with low biomass and dry matter yields. Similar results were obtained by Elizondo-Salazar and Espinoza-Fonseca[36], and Reyes, Mendez, Luna, Herrera, Guaman, and Espinosa-Coronel [37] when evaluating *C. nlemfuensis* in conditions of 1466-2229 mm, 17.9-25 °C and 86.88% relative humidity. These reported 1.77 and 0.75 $t.ha^{-1}$ of fresh biomass and dry matter. Hence, Roca, Zamora, Zamora, and Felix [38], and Mendez, Reyes, Luna, Verdecia, Espinoza,. Pincay, Espinosa, Macias, and Herrera [39] state that the structure of the species and the prevailing climatic conditions, mainly humidity, light and temperatures, directly influence the productivity of the species and varieties of pastures in the different periods of the year. In this way we can define that the biomass production capacity of pastures is related to the quality of the pasture, the animal consumption of the grass in grazing, and with the productive capacity of the pastoral systems.

Under conditions of the Pasco region, Peru (1500 mm, 15.5 °C, 92% RH), Lopez, Nunez, Aguirre, and Flores [40] reported superior results in DM production in *B. mutica*, *M. minutiflora* and *S. sphacelata* of 2, 1.5 and 0.88 $t.ha^{-1}$; those who attributed the variability of the results to the fluctuation of temperature (19; 19.78 and 22 °C) and the demands of evaporation and availability of water in the soil (26.8; 25.5 and 25.8%). These aspects are essential for the proper functioning of the photosynthetic activity of plant species that directly influence their growth and productivity.

In this sense, it is stated in the international literature that temperature and humidity show an inversely proportional relationship, because the higher the average temperature, the lower the soil humidity; product a: a greater loss of water by evaporation, hence the need for research on the effects of extreme phenomena in different phenological phases of crops to maintain the sustainability of agroecosystems. This statement agrees with the reports of Confalone, Vilatte, Aguas, Barufaldi, Eseiza, and Ponce [41], and Apraez, Galvez, and Apraez [42].

The third group was made up of *M. maximus* with medium to high values in CP, leaf/stem ratio, ISDMD, ME and medium values in the rest of the indicators. Similar results were reported by [39], in the regions of Empalme (225.6 mm; 25.8 °C; 86% RH) and Guayas (117.2 mm; 23.77 °C; 79% HR) with CP levels (11-12.39%); leaf/stem ratio (2.15-2.88); DMD (52-53%) and ME (6.12-7 MJ.Kg-1) and production of leaves higher than the stems in both conditions.

While Mendez, Reyes, Luna, Verdecia, Espinoza, Pincay, Espinosa, Macias, and Herrera [39] when evaluating the effect of the variety and the climatic zone in Megathyrsus (cultivars: Común. Tanzania and Tobiatá), only found interaction for the yield indicators and the leaf/stem ratio for the region with the highest rainfall in the Tanzania cultivar. For quality CP, DMD, ME, NLE; there were no differences between the varieties, but the effect of climate was found with the best values for the region with the least rainfall.

In this Hence, Roca, Zamora, Zamora, and Félix [38], Herrera [43], Herrera, Garcia, and Cruz [44], and Cuervo-Vivas, Santacoloma, and Barreto [45] pointed out that the elements of the climate interact and have a marked effect on the growth and development of the species and varieties of grasses in the different months of the year; we can explain that this behavior is due to the fact that plant species exist, reproduce and endure in certain edaphoclimatic contexts; what can be considered as tolerance to those conditions. These aspects are revealed in the present study due to the differences and similarities found in terms of quality indicators, in relation to their differences in growth habit, structure and phenology of the species under study.

The values of CP, digestibility and energy intake are in the range of what is reported in the literature [39], [46], [47]; when studying five varieties of *Megathyrsus maximus* (Common, Tanzania, Dwarf, Likoni, Mombaza and Tobiatá), they did not find significant differences when evaluating the effect of the variety on digestibility; in the cases reporting DMD higher than 47%, that behavior is attributable to the Constitutive similarities of the different cellular components of the plant depending on the variety.

The fourth group was formed by C. purpureus with the Maralfalfa and Elephant varieties with the highest yields (total biomass and DMY). Under conditions of the Ecuadorian Amazon [45] (1426 mm, 23.7 °C and 83.8%, rainfall, average temperature and relative humidity) reported values higher than 90 $t.ha^{-1}$ and 20 $t.ha^{-1}$ of biomass and dry material; respectively. These variations are given by natural causes or by human action such as: the availability of water, development of the root system of the plant and time of year; these produce morphological changes such as the decrease in leaf blades and the increase in vascular bundles, results that differ from those obtained in the current study: 81.3 and 26.46 $t.ha^{-1}$.

While under conditions of Valle of Cauto, eastern Cuba in salinity-tolerant varieties, Herrera [15] reported inferior results. Discrepancies with this study that are attributed to the fact that, there are specific conditions that are very different from the rest of Cuba and the tropics in Valle of Cauto, especially the climatic characteristics, such as higher temperatures, with more than 34 °C and less rainfall (790 mm), where the topography and types of soils are abundantly plastic, which makes their management difficult and makes them prone to salinization processes. On the other hand, Herrera [15] and Martínez and González [48] reported for the varieties CT-115, CT-169, Morado, King grass and the hybrids OM-22, H-1 and H-2; productions per cut during the period of low rainfall of 8-12 $t.ha^{-1}$. Those who report that DM production was higher in the dry season (November-May) when compared to the rainy season where rainfall reached 653 mm, which is below the historical average for the region and could affect the expected yield.

This corroborates that the behavior of rainfall, soil, planting time and other climatic factors can affect the behavior of one or another variety and change the order of merit between them. To make decisions about the variety to plant, other factors are important, such as the leaf-stem relationship, establishment, persistence and distribution of annual production [15]. On the other hand, Ray, Almaguer, Ledea, Benitez, Arias, and Roselle [49], when evaluating varieties of Cenchrus tolerant to drought, found a higher percentage of leaves and leaf area with respect to the parent and control (Cenchrus Cuba CT-115), which allows generating a greater amount of biomass, providing the animals with elements with higher nutritional quality. This research shows the adaptability of these varieties to the conditions of fragile ecosystems and in the process of degradation, very frequent in the current conditions of exploitation of livestock ecosystems in tropical regions such as the region under study.

C. purpureus x *C. typhoides* integrated the fifth group typified by low levels of CP, ISDMD, leaf/stem ratio, ME and elevated DM, NDF, ADF, lignin, Cel, Hcel, NDF/N and ADF/N ratios. . Results that coincide with those reported in varieties tolerant to drought in the Valle of Cauto region, Cuba by Ledea, Ray, La-O-Leon, and Reyes [50], Ledea, Verdecia, La-O-Leon, Ray, Reyes, and Murilo [51], and Ledea, La-O-Leon, Ray, and Vazquez [52] where they obtained increases in DM, NDF and decrease in CP with values of 7.6% CP, 77% NDF, 33% ADF, 37% Cel, 35.3% Hcel, OMD 44%, ISDMD 45%; without presenting differences between the varieties.

The increase in fibrous content is given by a greater number of stems than leaves, which brings with it an increase in structural carbohydrates. Thus, the decrease with the maturity of CP and digestibility could be due to the senescent process and the increase of the cell wall. This morphological behavior is characteristic of tropical grasses in response to climatic conditions and the effect of their rapid growth. This is one of the issues for which perhaps differences between the varieties of this genus were manifested; in addition to coming from the same parent and having similarities that impose a uniform response from the chemical point of view for the rumen degradability parameters of organic matter, the values were low. This is associated, according to Ledea, La-O-Leon, Ray, and Vazquez [52], due to the increase in the passage rate and the decrease in the digestion rate; which causes faster output of undigested organic matter from the rumen, and causes a tendency to decrease the total microbial yield, since this would generally increase if the amount of fermented organic matter is greater.

For their part, Valenciaga, Lopez, Delgado, Galindo, Herrera, and Montenegro [53], when evaluating the effect of Saccharomyces cerevisiae hydrolyze on the *in situ* degradability of DM, OM, NDF and ADF of *Cenchrus purpureus* cv. OM-22, reported increases as concentrations of this additive in the diet rose. The increase in the rumen degradability of the nutrients of the evaluated forage, with the increase in the amount of yeast enzymatic hydrolyze added to the diet, can be related to what has been written in the literature about the activating effect of yeast strains in populations of total viable bacteria and cellulolytic bacteria, when these strains are used as additives in ruminant diets.

IV. CONCLUSIONS AND RECOMMENDATIONS

The indicators with the greatest determination on the characterization of the grasses in the edaphoclimatic conditions of Los Ríos province, Ecuador, were the protein content, energy contribution, constituents of the cell wall, leaf-stem and nitrogen-cell wall relationships, which favor a decrease in quality as productivity increases.

The species with the greatest adaptability and behavior for the region were *Cenchrus purpureus* vc Maralfalfa and Elephant; *Brachiaria brizantha*, *Brachiaria hybrid* vc Mulatto I, *Megathyrsus maximus*, *Eriochloa polystachy*a and *Echynochloa polystachya*. Although the best behavior was presented for the group formed by Megathyrsus maximus with an adequate relation between production, chemical composition, and energy contribution.

It is recommended to consider all this information which would contribute to the design of technological alternatives for sowing, establishment, management and use of its biomass as a food source where productivity and sustainability of the ecosystem are minimized, in addition to conducting new research to assess the impacts of the proposed technological alternatives on livestock and the ecosystem.

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Internet of medical things. Measurement of respiratory dynamics using wearable sensors in post-COVID-19 patients

Internet de las cosas médicas. Medición de la dinámica respiratoria mediante sensores vestibles en pacientes posCOVID-19

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***Abstract*—Nowadays, the measurement of respiratory dynamics is underrated at clinical setting and in the daily life of a subject, still representing a challenge from a technical and medical point of view. In this article we propose a concept to measure some of its parameters, such as the respiratory rate (RR), using four inertial sensors. Two different experiments were performed to validate the concept. We analyzed the most suitable placement of each sensor to assess those features and studied the reliability of the system to measure abnormal parameters of respiration (tachypnea, bradypnea and breath holding). Finally, we measured post-COVID-19 patients, some of them with breath alterations after more than a year of the diagnosis. Experimental results showed that the proposed system could be potentially used to measure the respiratory dynamics at clinical setting. Moreover, while RR can be easily calculated by any sensor, other parameters need to be measured with a sensor in a particular position.**

***Keywords* - Respiratory dynamics, respiratory rate (RR), inertial sensors, wireless communication, post-COVID-19 condition.**

***Resumen*—Hoy en día la medición de la dinámica respiratoria está infravalorada en el ámbito clínico y en la vida diaria de un sujeto, y sigue representando un reto desde el punto de vista técnico y médico. En este artículo proponemos un concepto para medir algunos de sus parámetros, como la frecuencia respiratoria (FR), utilizando cuatro sensores inerciales. Se realizaron dos experimentos diferentes para validar el concepto. Analizamos la colocación más adecuada de cada sensor para evaluar esas características y estudiamos la fiabilidad del sistema para medir parámetros anormales de la respiración (taquipnea, bradipnea y retención de la respiración). Por último, realizamos mediciones en pacientes posCOVID-19, algunos de ellos con alteraciones respiratorias después de más de un año del diagnóstico. Los resultados experimentales mostraron que el sistema propuesto podría utilizarse potencialmente para medir la dinámica respiratoria en el ámbito clínico. Además, mientras que la FR puede calcularse fácilmente con cualquier sensor, otros parámetros deben medirse con un sensor en una posición determinada.**

***Palabras Clave* - dinámica respiratoria, frecuencia respiratoria (FR); sensores inerciales; comunicación inalámbrica; condición posCOVID-19.**

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I. INTRODUCTION

THE breathing mechanism is a complex behavior driven by control systems that regulate ventilation. The aim is to respond optimally to the prevailing metabolic needs and to various demands on the respiratory apparatus. Actually, there is an automatic control system permanently aimed at maintaining the arterial pH, 0_2, and $C0_2$ pressures ($Pa0_2$, $PaC0_2$) within the range of normal values. In addition, various systems can disrupt the automatic regulation in order to use the respiratory system in nonrespiratory tasks such as speech, singing, vomiting, and coughing, among others.

According to Milic-Emili [1], the brief has three parts, each one is driven by different neural circuits: the inspiratory phase, the expiratory phase I, and the expiratory phase II. During the inspiratory phase, the burst neurons shoot to the inspiratory ramp neurons and after a time, the switch-off neurons finish the inspiratory phase and immediately starts the expiratory phase I, this phase is a inhibiting activity because it counteracts the initially strong elastic recoil of the chest and slows down the rate of exhalation in the first part of expiration. During expiratory phase II the inspiratory muscles are inactive allowing passive expiration. Expiratory muscles, such as abdominal muscles and internal intercostals, are recruited only in cases of increased ventilatory drive. The upper airway dilator muscles are generally activated significantly earlier than the pump muscle in order to allow the airways to be dilated before any negative intrathoracic pressure is created.

The briefing is a complex system with extremely high precision in its operating mode.

The measurement of respiratory dynamics includes parameters, such as respiratory rate (RR), respiratory tidal volume, depth of breath, inspiration and expiration time. The measurement of these parameters in both at clinical setting and in the daily life, could be used for early diagnosis, prognosis, and prevention of many diseases such as heart attack, stroke or depression, among others [2], [3].

In particular, the measurement of human respiration is a key factor in the diagnosis, monitoring and rehabilitation of respiratory disorders [4]–[7]. On the other hand, RR is also a vital signal and it can predict abnormalities in the homeostatic equilibrium [6], [7]. Furthermore, Cretikos *et al*. [7] and Massaroni *et al*. [8] suggest that it is possible to predict physiological distress, anxiety, depression and panic attacks, obstructive and central sleep apnea, bronchitis, asthma, and other potentially serious adverse events.

Nowadays, the detection of RR at clinical setting is made through auscultation or observation, counting the number of breaths made in a minute (bpm). However, this method has low credibility and can be ignored by the clinicians, or simply overlooked and under-recorded [7]. To overcome this limitation, different studies have been carried out in the area, both at the level of contact-based methods and non-contact methods [8].

At clinical setting, spirometry or pneumotachograph methods are also used to measure parameters related to human breathing. The measurement is made with the help of a mouthpiece or face mask [9]. Although these methods have a good accuracy rate, they also have limitations, since they are not ergonomic and are intrusive, not allowing to a comfortable continuous monitoring.

Since the last decade, the research community has been working in the development of novel technologies and methodologies to overcome the limitations of current procedures [9]–[24]. Wearable sensors such as accelerometers, gyroscopes and inertial measurement units (IMUs) arise like a potential alternative to measure the respiratory parameters; however it is still a challenge in a medical and technological point of view [8].

The use of accelerometers for the measurement of respiration has been subject to a wide study, usually subject to validation. As far as RR is concerned, the use of accelerometers has been widely studied, both at the level of the upper thorax and/or abdomen [12], [13]. Furthermore, some authors ([8], [12], [13], [17], [25]) have suggested that the use of triaxial accelerometers allows the measurement of acceleration regardless of the orientation of the body, which removes the need to pay attention to the alignment of the sensors with the largest axis of rotation characteristic of singles-axis or dual-axis accelerometers.

Despite the evolution over time in terms of accelerometers, they still have some limitations, namely the fact that they only adapt to static situations. In this sense, it seems that there is a general consensus that inertial sensors could avoid the accelerometers limitation if data provided by the gyroscope are also included, thus allowing adaptation to dynamic situations.

For instance, Heba Aly and Moustafa Youssef [5] proposed a low-cost smartphone-based robust respiratory rate estimator called Zephyr. In this research, it was demonstrated that the values of the accelerometer and gyroscope sensors of a smartphone placed on the chest of the subjects are affected by the breathing mechanism. This breath rate estimator includes an algorithm that filters out noisy signals as imputed, but also performs a fusion of the sensors in order to increase the accuracy of the estimator. Following the same line of thought, Ja-Woong Yoon et al. [21] proposed a system to improve the measurement of respiratory rate of individual accelerometer or gyroscope through a fusion sensor with Kalman Filter.

In Elfaramawy *et al*. [19] a wearable patch sensor network to measure the breathing rate and the frequency of coughing is proposed. This system uses wearable wireless multimodal patch sensors, a low-power 9-axis IMUs and a MEMS microphone. In a more recent study, Elfaramawy *et al*. [20] used data processing and fusion algorithms to calculate the respiratory frequency and the coughing events in a more accurate way.

Ambra Cesareo et al. [9], [22] presented a wearable contact-based device for respiratory rate assessment that uses 3 IMUs (two units are placed on the thorax and one on the abdomen). In order to compensate the high levels of noise of the accelerometers and the tendency to drift over time of the gyro, an implementation of a filter proposed by Madgwick was made [26]. This implementation allowed the representation of the respiration using quaternions, like the system proposed by Simon Beck et al. [23]; however, this system only uses two IMUs: one located in the ventral area, while the other is located in the dorsal area over the chest.

James Skoric et al. [24] developed a system that uses an IMU which pairs a 3-axis acc and a 3-axis gyro for recording SCG (a method of recording cardiac vibrations with an accelerometer that can also be used to extract respiratory information).

On March 11, 2020, the World Health Organization (WHO) declared the novel severe acute respiratory syndrome coronavirus (SARS-CoV-2) infection a pandemic [27]. Severely affected COVID-19 cases experience high levels of proinflammatory cytokines and acute respiratory dysfunction and often require assisted ventilation.

Taking into account the pandemic situation, its symptoms and the previous scientific results related to measuring respiratory dynamics, we propose an alternative technique that is non-invasive, ergonomic, wearable, and wireless system based on four commercial inertial sensors to measure *automatically* the respiratory dynamics.

The main objectives of our research are to define a reproducible procedure to measure respiratory parameters and to objectively evaluate the advantages and drawbacks of inertial sensors available in the market. In order to do that, we selected the most suitable wireless and ergonomic sensors considering the price/quality ratio. We measured respiratory dynamics in both, healthy and post-COVID-19 conditions. While the first is to replicate the current manual procedure followed at clinical practice, the second is to validate the reliability of the proposed concept with post-COVID-19 patients.

This article is organized as follows: Section II presents the materials and methods used in our research, where we described the concept, the technology used for the measurement (software and hardware) as well as the main data related with the groups of healthy volunteers and post-COVID-19 patients used to validate the main hypothesis. Section III describes hypothesis and shows the results, while the discussion is made in Section IV. Finally, the main conclusions of this research and the future steps are presented.

This research is authorized by the ethical committee of Universidad Politécnica de Madrid and all volunteers signed the informed consent.

II. Materials and Methods

In this section we describe our conceptual setup based on inertial sensors. The concept was validated with healthy volunteers and post-COVID-19 patients.

Due to the fact that the inertial sensors used are not certified as medical devices, before measuring patients, a group of healthy volunteers was selected (without diagnosis of brief pathology) in order to compare the measured values with the medical literature to ensure the reliability of the data. Moreover, we validated the number of sensors that should be used and the position in the abdominal area and rib cage.

The objective was to evaluate the numbers of sensors to be used, the reliability of IMUs to measure the respiratory dynamics, the quality of the bluetooth connection, the usability of the designed software interface, and the ergonomic characteristics of the measuring system, among others.

On the other hand, it is also necessary to ensure that the sensors are well coupled to the subjects, not causing discomfort and promoting measurements with reasonable accuracy. Through literature consultation, the coupling chosen were sensor-skin adhesives, due to its hypoallergenic and non-sensitising properties.

A. Software and Hardware architecture

The system is composed of four sensors from MetaMotionC. Each one is a 9-axis IMU, that is a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer.

This sensor was mainly selected due to its weight and size (approximately 25 mm in diameter); in order to non inhibit or influence on the normal breathing pattern of each subject, then the ergonomic aspect of the sensor was considered.

Regarding communication options, sensors are based on a Buetooth Low Energy (BLE) module and an ARM Cortex-M4F MCU. As previously mentioned, each sensor is able to communicate with a gateway devices. On the other hand, data from the sensor can also be saved in a flash memory. A SDK tool is provided to calibrate the sensor and to monitor the calibration status.

The location of the sensors has been determined by the body's anatomy and the respiration dynamics. The four sensors are placed in the trunk. The first one is located in the sternum. The second one in the diaphragm, following a vertical line down the sternum, just above the belly button. The other two sensors are located on both sides of the trunk (intercostal muscles), following the midaxillary line. The height of these last sensors is found between the two previous ones located in the sternum and the diaphragm.

Figure 1 shows the setup concept. The data acquired from the sensors were sent to the MetaHub Gateway (Raspberry Pi) via BLE communication protocol and from there to a conventional computer for further analysis. A scheme to this setup is presented in Figure 1.

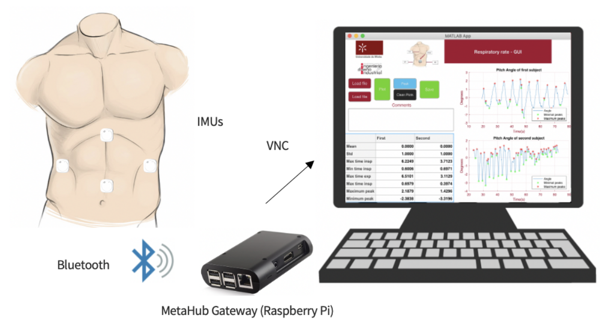


Fig. 1. Developed system and its graphical user interface.

At this stage, algorithms were developed in order to assess breathing patterns and the corresponding respiratory rate using the Raspberry Pi. The algorithms were developed using the Python Programming language.

The Euler angles (EA), Pitch, Roll and Yaw, were figured it out for each sensors and saved in an excel file. Because the output requires a fusion of the sensors (Accelerometer and Gyroscope), a Kalman filter was implemented. The update rate is 100 Hz. The flowchart in Fig. 2 summarized the processing signal algorithm.

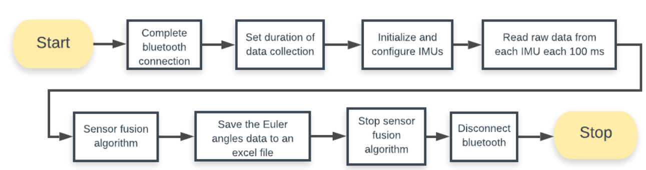


Fig. 2. Euler angles data system acquisition process.

III. Data filtering, visualization and feature extraction

IMUs are affected by different errors, such as offset and bias. In order to reduce these errors, before data acquisition, the sensors were calibrated using the SDK tool provided by Mbientlab. On the other hand, a Kalman filter was implemented to reduce these limitations.

After the recording, all data was processed in Matlab. Figure 3 shows the flowchart of the overall signal processing. We applied a linear detrend to all measured data to compute the respiration rate and used a Low-pass filter and a second order fitting Savitzky–Golay smoothing filter to reject both high frequency and noise peaks that can be generated by motion artifacts.The Savitzky-Golay filter also facilitates the identification of the Minimum and Maximum peaks. Data were normalized using z-score procedure.

Once the signal is filtered, an analysis of the respiratory signal is made over time in order to identify the peaks and valleys, which represents a whole respiratory cycle. With this, it is possible to retrieve the respiratory frequency of the signal, as well as features related to the breathing pattern.

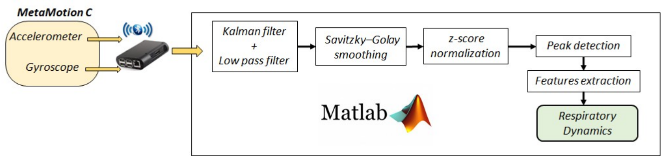


Fig. 3. Signal processing flowchart.

A. Software Interface

In order to monitor the respiratory dynamics, an interface was developed under Matlab environment. A scheme of the interface is showed in Figure 4. As it can be observed, the application has different interactive options, such as buttons, graphics, text area and table with different purposes. All these functionalities are described bellow.

The data obtained are shown in two intuitive ways: graphically and numerically, making easy to compare or monitor the respiratory rate in real time. Moreover the visualization area can be cleaned after that and the data can be saved. A box dialog was included for writing medical opinion/analysis related with the data. This information might be included in the medical history of the patient.

As a first step, the user must click on both buttons (Load File) related to the importation of excel files. In order to complete this step, the user must select the excel files to be compared. Once selected, the files will be imported and are ready to undergo the next steps of the process.

After importing the files, there is a button (Plot) with the functionality of filtering (Low pass filter and Savitzky-Golay filter), normalising the data through z-score and then placing it on the two graphs; filters were tunned experimentally.

Although a comparison is already possible by viewing the graphs, this comparison is made easier when another button is pressed. There is another button (Peak) that allows the maximum and minimum peaks to be displayed, as well as extracting the relevant features and displaying them in a table.

If the user wishes to compare two new graphs, it is only necessary to use the button (Clean Plots) for cleaning the graphs and proceed with the whole process with the new data.

The functionality to create comments for professionals is ensured through the creation of a text area, where the professional can save comments about the graphs, subjects or about the difference between the two graphs.

In order to save the data related to the features, as well as the comments made by the professionals, the ”Save” button was created, which as soon as it detects a click saves the features data and the comments in an excel file and in a text file, respectively.

B. Healthy volunteers and Patients

The participants were divided in three groups according to the experimental necessities of our project. The group 1 (G1), healthy volunteers, participated in the validation of the reliability of concept, while group 2 and 3 (G2 and G3, respectively) participated in the respiratory data dynamics validation. In the following paragraphs, we present the most relevant demographics and clinical data for each group. All participants were included after written informed consent.

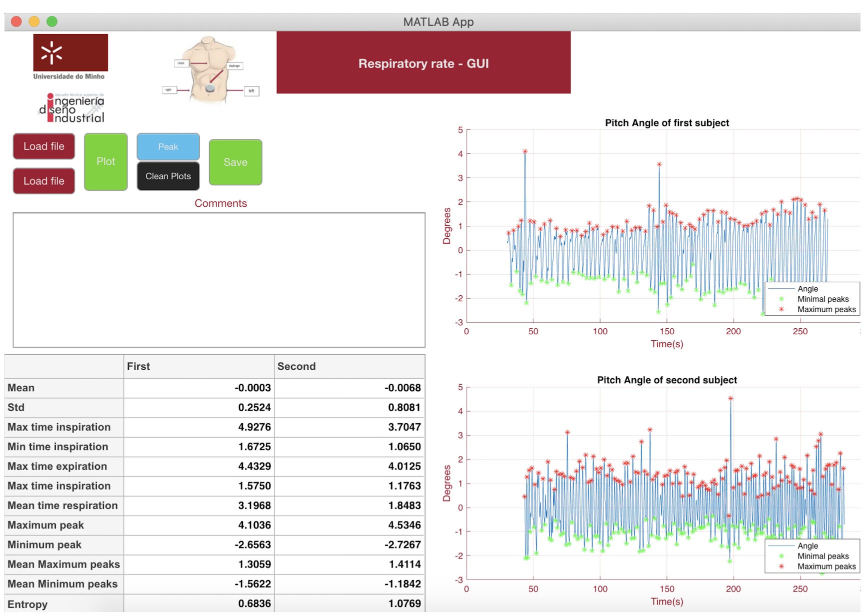


Fig. 4. Matlab GUI after the feature extraction.

For G1 group, 20 volunteers (15 men and 5 women) without respiratory disease history or COVID-19 diagnosis were recruited from university staff and family. The population were (mean ± standard deviation): age 25.650 ± 12.097 years, weight 66.400 ± 12.435 kg, with a height of 168.100 ± 9.402 cm. In this group, 65% of the subjects were students, 40% practice sports at least once a week, 30% were smokers and only 20% had some kind of respiratory problem (rhinitis, sinusitis, and bronchiolitis as a child).

In G2 group, 10 post-COVID-19 patients were selected from the *Patient Affected by COVID-19 Disease Association* (AMACOVID), Madrid. Two subjects were excluded after the data analysis due to noise and communication issue, therefore data from 8 participants (3 men and 5 women) were finally included in the analysis. The post-COVID-19 population were (mean ± standard deviation): age 49.556 ± 9.1422 years, weight 74.333 ± 19.293 kg, with a height of 164.0 ± 7.272 cm. Tables I and II summarize the most relevant demography and clinical data including a list with the daily activities.

TABLE I
GENERAL INFORMATION ABOUT POST-COVID-19 PATIENTS

Patient-ID	Age	Sex	Height (cm)	Weight (kg)
VAMA02	54	M	175	80
VAMA03	28	F	156	105
VAMA04	44	F	156	56
VAMA05	60	M	170	85
VAMA06	49	F	165	56
VAMA08	46	F	167	93
VAMA09	54	M	170	90
VAMA10	52	F	152	52

Table III shows the most relevant data related to the clinical history of each patient.

Table IV summarizes the symptoms suffered by the patient including the diagnosis date. The PCR-test (real-time reverse transcriptase-polymerase chain reaction) was used to diagnose the disease. Fever and pneumonia were the most common clinical symptoms. Other symptoms reported by patients were: hair and skin problems, headache, vomits, and cough, among others.

Table V summarizes the symptoms suffered by patients after COVID-19 disease, however, some of these symptoms are still present today. Other symptoms reported are: speech problems and lost of force in the muscles of the extremities.

Finally, G3 group consisted of 5 (2 men and 3 women) healthy volunteers (HV), without diabetes, heart, lung and brain diseases. Demographic data were (mean ± standard deviation): age 28.600 ± 12.706 years, weight 64.600 ± 12.831 kg, with a height of 167.0 ± 10.351 cm. Table VI summarizes the most relevant demography and clinical data while Table VII shows the daily life activities.

TABLE II
MAIN DAILY-LIFE ACTIVITIES

Patient-ID	Smoker	Laboral Activity	Recreative activity	Sport
VAMA02	No, never	Commercial tasks	Read, write	Run, walk
VAMA03	No, never	Housewife	No	No
VAMA04	No, never	Housewife	No	No
VAMA05	Past (22 years)	Caretaker and maintenance	Dance, paint	No
VAMA06	10 cigarettes a day	Cleaner	No	No
VAMA08	Past (1 year)	Call center	No	No
VAMA09	Past (9 years)	Worker	No	Walk
VAMA10	Past (19 years)	Call center	Paint, write	No

TABLE III
MEDICAL HISTORY BEFORE COVID-19 DIAGNOSIS

Patient-ID	Heart disease	Respiratory disease	Allergies
VAMA02	Arrhythmia	No	Pollen, pet hair
VAMA03	No	Asthma	Seafood, spices
VAMA04	No	No	No
VAMA05	No	Apnea	No
VAMA06	No	No	Pollen
VAMA08	No	No	No
VAMA09	No	No	No
VAMA10	No	No	Pollen, pets hair

TABLE IV
CLINICAL PICTURE UPON DIAGNOSIS

Patient-ID	Diagnosis Date	Diarrhea	Pneumonia	Fever	Smell-Taste
VAMA02	04/04/2020	X	X	X	X
VAMA03	12/03/2020	-	X	X	-
VAMA04	17/12/2020	-	X	X	X
VAMA05	03/09/2020	-	X	X	-
VAMA06	29/12/2020	-	-	X	-
VAMA08	15/09/2020	-	-	X	X
VAMA09	02/12/2020	-	X	X	-
VAMA10	15/03/2020	X	-	-	-

TABLE V
SYMPTOMS AFTER DISEASE

Patient-ID	Breathing problems	Heart problems	Memory problems*
VAMA02	X	Arrhythmia	-
VAMA03	X	Tachycardia	X
VAMA04	-	-	X
VAMA05	X(walking)	-	-
VAMA06	-	-	X
VAMA08	-	-	X
VAMA09	X	-	X
VAMA10	X(chest pressure)	-	X

* Subjective memory complaints

TABLE VI
INFORMATION ABOUT THE HEALTHY VOLUNTEERS (HV)

ID-HV	Age	Sex	Height (cm)	Weight (kg)
N1	22	F	156	47
N2	22	F	160	52
N3	22	M	179	74
N4	23	M	180	70
N5	54	F	160	80

All participants were sitting with their backs straight and motionless for the study. Two different tests were carried out. The first recording lasted exactly 1 minute, while the second test lasted 4 minutes. In the first test, participants were told to perform deep breaths at a regular pace, while in the second test, the measurements were recorded in a resting state. The participants were informed to breath normally and not to talk during the measurement. No other instructions were given to the subjects to regulate the rate or depth of their breaths. In the second experiment, participants were asked to sit down and stay quite 15 minutes before the measurement [1].

C. Results

During the measurement, all volunteers were sitting down with the backs against the backrest. In the presentation of the results, the roll angle was used since it presents the most reliable values.

D. Experiment 1: Concept Validation

This experiment was performed at ETSIDI-UPM Mechatronics Lab with volunteers from G1 group. Some hypothesis to validated:

- Number and position of inertial sensors (see Section 2).
- Reliability of Bluetooth communication considering the number of sensors.
- Reliability of each sensor to measure respiratory dynamics.
- Autonomy and data storage capabilities.
- Software testing.

After each sensor was placed in the target position, the volunteer was encouraged to deeply inhale and exhale during one minute. At the same time, the respiratory rate was manually counted by the number of the chest rise. In order to proceed with the comparison, the respiratory rate of each IMU was computed (Fig. 3). Respiratory rate (manual and automatic) are summarized in Table VIII.

We defined k_i, with $i = 1, ..., m$ the set of the roll angles of an inertial sensor during a measurement procedure.

TABLE VII
DAILY LIFE ACTIVITY (HV)

ID-HV	Smoker	Laboral activity	Recreative activity	Sport
N1	No	Student	X	Yoga
N2	No	Student	No	No
N3	Yes (2 cigarettes per day)	Student	No	No
N4	No	Software engineer	Read, sing	Soccer, gym
N5	Yes (1/2 cigarettes per day)	School monitor	No	Fitness

TABLE VIII
RESPIRATORY RATE MEASUREMENT IN GROUP 1. COMPARISON BETWEEN MANUAL AND AUTOMATIC PROCEDURE.

Subject	Chest (bpm)	Diaphragm (bpm)	Left (bpm)	Right (bpm)	Manual (bpm)
1	12	10	12	13	12
2	14	12	14	14	14
3	15	15	15	13	15
4	15	15	14	12	15
5	22	21	22	20	22
6	14	14	14	14	14
7	27	21	25	25	27
8	10	10	10	10	10
9	17	19	19	19	19
10	19	19	15	18	19
11	16	16	15	16	17
12	9	9	10	9	9
13	17	17	17	17	17
14	16	16	17	17	17
15	13	13	14	14	14
16	17	14	17	17	17
17	12	12	12	12	12
18	14	14	14	14	14
19	12	14	12	14	14
20	6	7	6	7	6

M_j and m_j represent the sets of maximum and minimum values of k_i, respectively:

$$M_j = max(k_i), j = 1, ..., n \tag{1}$$

$$m_j = min(k_i), j = 1, ..., e \tag{2}$$

We computed the absolute error for each sensor by (3):

$$e_{abs} = \frac{\sqrt{(RR_m - RR_a)^2}}{n * (n-1)} \tag{3}$$

Where RR_m is the manual count as it is done at clinical setting, then it is considered the true value. RR_a is computed by the number of maximum peaks during 1 minute (See Fig. 3);

$$RR_a = \sum_{t=0}^{t=60} M_j \tag{4}$$

The absolute errors are: $e_{chest} = 0.0289$ for the chest sensor, $e_{diap} = 0.1368$ for diaphragm sensor, $e_{left} = 0.0316$ for the left sensor and $e_{right} = 0.0342$ for the right sensor. Taking into consideration the range of respiratory rate for healthy volunteers, $12 - 20$ breaths per minute, any sensor can be used to measure respiratory rate accuracy [6], [28].

Moreover, some volunteers were encouraged to simulate the most common pattern of breathing *Tachypnea*, where $RR >$ 20 breaths per minute, *Bradypnea*,where $RR < 12$ breaths per minute and finally to hold-breath, where the inhaled air is kept off some seconds [18]. Values measured by chest sensor are presented in the Fig. 5. The reader is advised to consult the supplementary material to view the data measured by the other inertial sensors, which are noticeably affected by measurement noise.

E. Experiment 2: Post-COVID-19 patients measurement

Experiment 2 consists in measuring the respiratory dynamics during 4 minutes to G2 and G3 groups. G2 was measured at the COVID-19 patients association. Some extra hypothesis to validated in this experiment are:

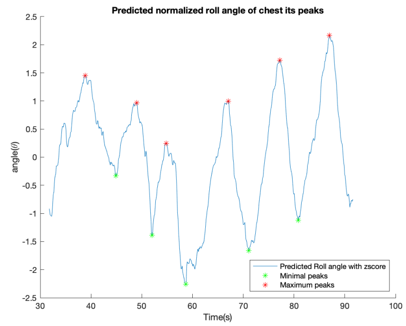
- Difference in the measurements given by each sensor.
- Difference in respiratory rate values between the groups.
- Difference in the breathing patterns of the groups.

The features that best describe the respiratory dynamics are compared between groups: mean time of respiration, $\overline{b_t}$, [sec], the mean of maximum peaks $\overline{peak_{max}}$, [°], the mean of minimum peaks $\overline{peak_{min}}$, [°] and the respiratory frequency b_{freq}, [bpm], that is the number of breaths per each minute.

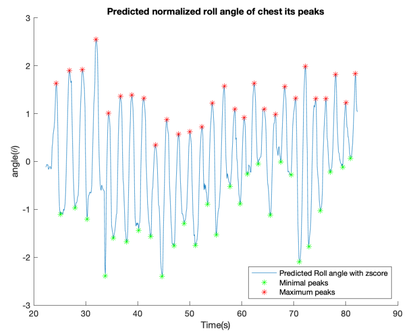
By considering (1) and (2), the *time of respiration* is defined as the elapsed time between two consecutive maximums (minimum), that is:

$$b_t = t_{K_{j+1}} - t_{K_j} \tag{5}$$

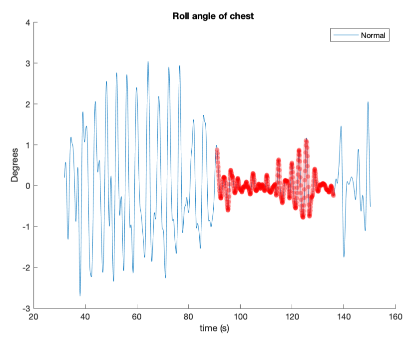
Where t_{K_j} and $t_{K_{j+1}}$ represents the time correlated to two consecutive maximum or minimum peaks.



(a) bradypnea



(b) Tachypnea



(c) breath

Fig. 5. Measurement of the most common breath patterns. Pattern recorded by chest sensor.

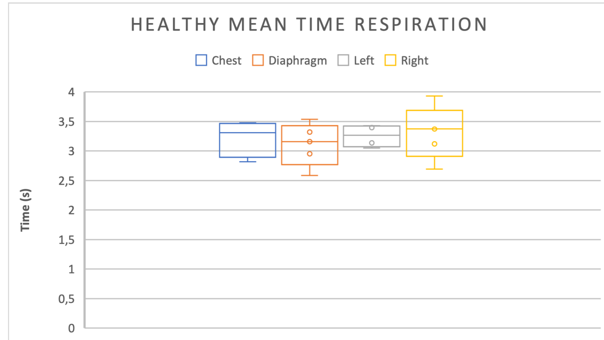
Then, the *mean time of respiration* is defined as the mean of all the time elapsed between two consecutive maximums (minimum), that is:

$$\overline{b_t} = \frac{1}{n-1}\sum_{i=1}^{n-1} b_t \tag{6}$$

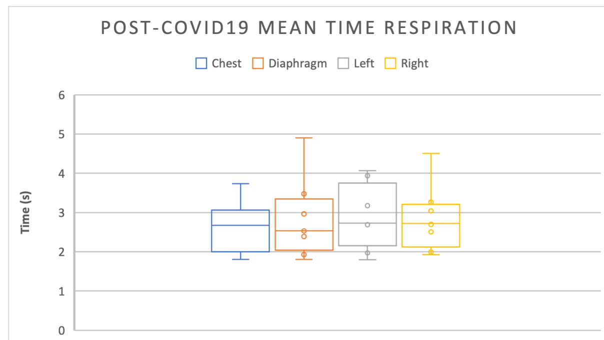
Finally, the mean of maximum and minimum peaks are defined with the following equations.

$$\overline{peak_{max}} = \frac{1}{n}\sum_{j=1}^{n} M_j \qquad \overline{peak_{min}} = \frac{1}{e}\sum_{j=1}^{e} m_j \tag{7}$$

Figures 6 to 9 show the measured features in both groups. As it can be observed from these Figures, the proposed system is able to capture differences in the respiratory dynamics between groups. The four sensors measured alterations in the breath behaviors, that is, the data recorded at each sensor shows significant differences between them.

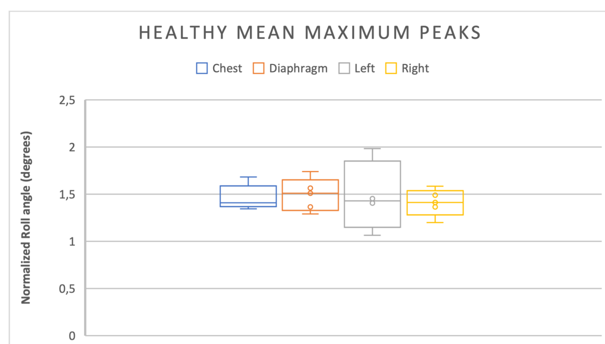


(a) Healthy volunteers

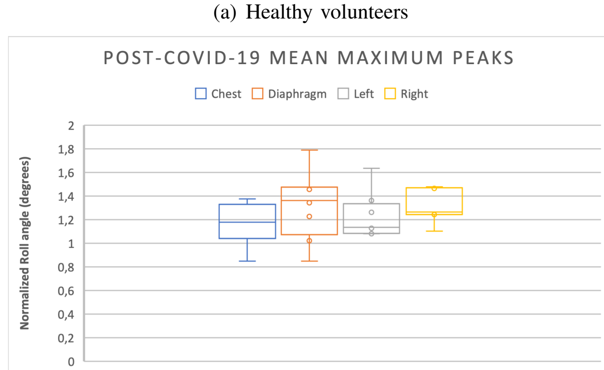


(b) Post-COVID-19 patients

Fig. 6. Mean value in *time respiration* features.

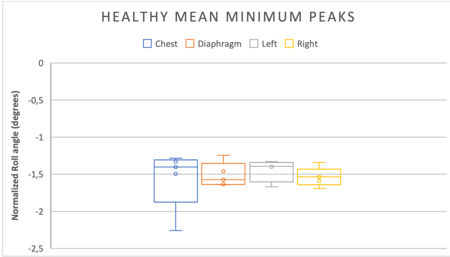


(a) Healthy volunteers

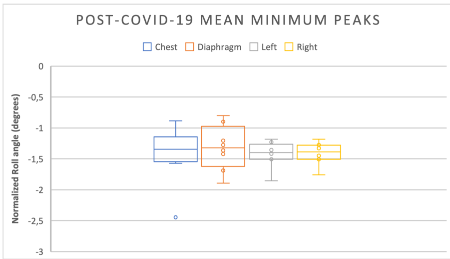


(b) Post-COVID-19 patients

Fig. 7. Mean value in *maximum peak* features.

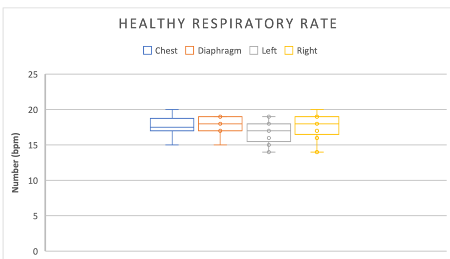


(a) Healthy volunteers

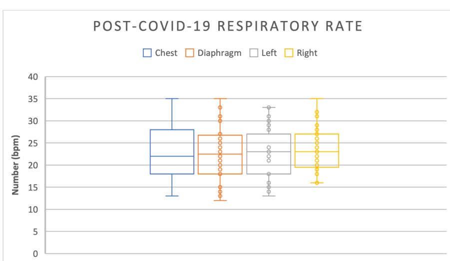


(b) Post-COVID-19 patients

Fig. 8. Mean value in *minimum peak* features.



(a) Healthy volunteers



(b) Post-COVID-19 patients

Fig. 9. Mean value in *respiratory frequency* features.

In order to compute the $p-values$, we just considered those post-COVID-19 patients who had alteration in RR. After choosing the data to be used, we applied an ANOVA test to compute the level of significance for each feature and sensor. Related to RR feature, the inertial sensor could be placed in any part of the abdomen and thorax ($p_{value} < 0.001$) as it was demonstrated in experiment 1. To measure the minimum time of respiration, right sensor is the most confident $p_{value} < 0.006$, while chest sensor, left and diaphragm sensors have $p_{value} < 0.01$. It is recommended to measure the minimum peaks using the right sensor, since it shows the $p_{value} < 0.05$, while no significant values were found for the other sensors. For measuring the maximum peaks, right sensor, again, seems to be best one with a $p_{value} < 0.05$ and non significant values were found for chest, diaphragm and left sensor.

IV. Discussion

A. Reliability of inertial sensors to measure respiratory dynamics

According to the experimental results, the potential of using multiple, wearable and ergonomic inertial sensors with bluetooth communication is suitable to measuring the respiratory dynamics. However, some drawbacks were found and we discuss about them below.

The position of each sensor needs to be deeply studied and correlated with abdominal and thorax muscles synergies. Although the sample size is a limitation in our study, the experimental results evidence that some sensors are more reliable than other to measure particular features of the respiratory dynamics beyond the RR. However, for measuring the RR, the inertial sensor could be placed in any abdominal or thorax area. Moreover, we did not find any correlation between the features measured by each sensor with the weight, height or body mass index in healthy volunteers.

The first experiment allowed to verify whether the sensors had enough sensitivity to measure the respiratory rate as well as to measure the most typical abnormalities in the respiratory pattern such us bradypnea and tachypnea. Moreover, a phase of hold-respiration was also measured and, under this situation, we determined the lower limit of the sensor's confidence interval for inhalation and exhalation stages of the breath. In Fig. 5 we presented data recorded by the chest sensor. In the supplementary material, the reader can observe that the other 3 sensors also reproduce the pattern, however, in some cases with more noise. The placement of these sensors may be related to the anatomy and fat distribution in the abdominal zone.

Although working correctly, the bluetooth communication is prone to failure with the time and battery consuming. However, there are still some areas that should be studied and improved before starting to use this method to measure the respiratory dynamics. Indeed, this study is limited to a controlled environment and low number of tests where subjects were constrained to a motionless sitting position. In a real-world scenario, additional filtering and processing would be required to remove motion artifact and noises from the signal.

Despite of being one of its main advantages, the bluetooth connection also introduces some difficulties when measuring. The first one is the time required for having the four sensors connected. This process is made manually (one by one), so the total time necessary for this activity increases to almost one minute. Additionally, when the last sensor becomes ready to start the measuring process, the first one has been bound for some seconds with the risk of not having the four sensors starting the measurement at the same exact moment. Furthermore, the BLE signal is weak with the clothes occlusion, which is a great limitation to measure respiratory dynamic in daily life, as well as the low autonomy of the system that is limited to 4-5 hours maximum.

Another limitation of measuring the respiratory dynamics with inertial sensors is the fact that the anatomy of men and women is different, specially referring to the fat distribution. Women have more body fat than men, which provokes that the movement done by the trunk while breathing varies between both sexes, specially in the chest area, where the distribution and the quantity of fat is different and superior in female.

This idea of fat distribution affecting the measurements is also relevant for people suffering obesity. When measuring these patients, the signal obtained is not as precise as with the rest of subjects due to the influence of the fat when performing the breathing movement.

For the experiments performed, the sensors were fixed using surgical tape, but in some cases the sensors did not stay still and were not completely fixed to the skin so the data obtained needed to be filtered to remove non real movements. To prevent this unwanted activity some artifacts like elastic bands, belts or suits should be developed to stick the sensor directly to the skin and collected data from the real movement.

B. Reliability of inertial sensors to measure alterations in respiratory dynamics under disease condition

Rapid breathing can be the result of anything from anxiety or asthma, to a lung infection or heart failure. Therefore to validate our proposal to measuring respiratory dynamics, patients diagnosed with post-COVID-19 condition were measured. As it is well know, one of the main clinical picture is pneumonia. However, in this proof of concept, we included three patients who did not suffered pneumonia during the disease (see Table IV) and one of them with subjective breathing problem in post-COVID-19 stage (see Table V).

The respiratory dynamics were measured during four minutes and results were compared with the control group, G3. By analyzing the results given in Figs. 6 to 9, patients who suffered pneumonia during the disease still had breathing problems and the respiratory rate was in the range of tachypnea, similarly to the patient who reported breathing problem in the post-COVID-19 stage. Furthermore, these high respiratory rate values were usually indicative that the ability of the subject to get oxygen into the blood and get carbon dioxide out becomes less efficient, causing the number of breaths per minute to increase.

On the other hand, by analyzing the peaks of the breathing graphs, it was found that post-COVID-19 subjects did not take such deep breaths when compared to healthy subjects, since the amplitudes of their peaks were lower, on average.

The differences in the respiratory dynamics in patients and control group was captured by the system. By comparing each sensor in both groups, we found significant differences that were related with the long-term consequences of the COVID-19 condition, even when the patient did not suffer from pneumonia. In this case, the alteration of the breath was not necessarily related with lung problems.

While the results presented are promising, better characterization and understanding of the reliability of the system is still needed before it can be used at a clinical level. This validation would be quite relevant, since it would facilitate the monitoring of normal and high-risk patients in a non-invasive way (post-COVID-19 condition, asthma, or chronic obstructive pulmonary disease, among others).

V. CONCLUSIONS

In this article, we have presented a novel concept to measure the respiratory dynamics using four wireless inertial sensors. We validated it by two different experiments, the first one aimed to automatize the current manual procedure at clinical setting. The main conclusion was that a single sensor can be used to measure the RR and, most important, it could be placed in any area of the abdominal or thorax part. Moreover, abnormal patterns of the respiration can be captured in a single measurement. In this case, the chest sensor shows more reliable results compared to the other sensors. One of the reasons may be the factor that the chest sensor was placed in a more stable zone minimizing the noise of the measuring.

In the second experiment, the main objective was to demonstrate that inertial sensors have enough sensitivity to capture alterations in respiratory dynamics. Post-COVID-19 patients were tested. The results demonstrated that there are alterations in the respiratory pattern in all sensors compared with the healthy volunteers.

The most relevant parameters of respiratory dynamics are computed automatically by a software developed in this research and they are conveniently presented to the medical staff using a human-machine interface designed and implemented under MatLab environment.

The main limitation of this study was the size of the groups included in the experiments. However, taking in consideration that it is a proof a concept, the results are promising and suggest that further studies are necessary for the full validation of the system.

In futures studies, issues related with autonomy of the sensors, wireless communication, relation between muscle synergies and data recorded should be studied deeply in order to get a better understanding of the respiratory dynamics. Also, an extended validation of the proposed system is needed also in dynamic conditions, during daily activities, considering both healthy subjects and patients with respiratory diseases.

In all experiments, we followed a strict protocol for cleaning common areas and materials between each use, in order to keep researchers and participants safe.

APPENDIX

A. Supplementary

The response of the four inertial sensors to different breathing patterns, such as Bradypnea (Figures S1 and S2), Tachypnea (Figures S3 and S4) and hold-respiration (Figures S5 and S6) were shown in the supplementary information.

B. Author contributions

Conceptualization, L.S., C.E.G.C., C.S., D.G.A., F.H.D.P. and J.B.L; methodology, C.E.G.C., L.S. and R.S.P.; software, L.S.and M.M.; validation, L.S., C.E.G.C., and M.M.; formal analysis, L.S. and C.E.G.C.; investigation, L.S., C.E.G.C.,and M.M.; writing original draft preparation, L.S., C.E.G.C. and M.M.; project administration, C.E.G.C. All authors have read and agreed to the published version of the manuscript

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D. Data availability

The data sets generated during the current study are available from the corresponding author upon reasonable request.

E. Conflicts of interest

The authors declare no conflict of interest.

F. Acknowledgments

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SUPPLEMENTARY MATERIAL

BRADYPNEA PATTERN:

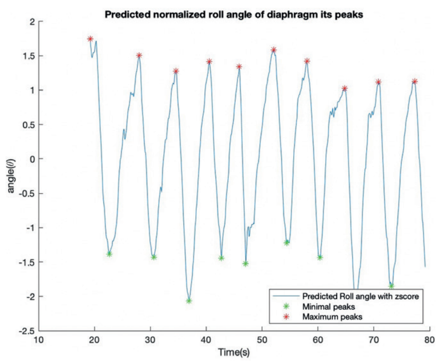

Fig. S1. Inertial sensor placed on diaphragm

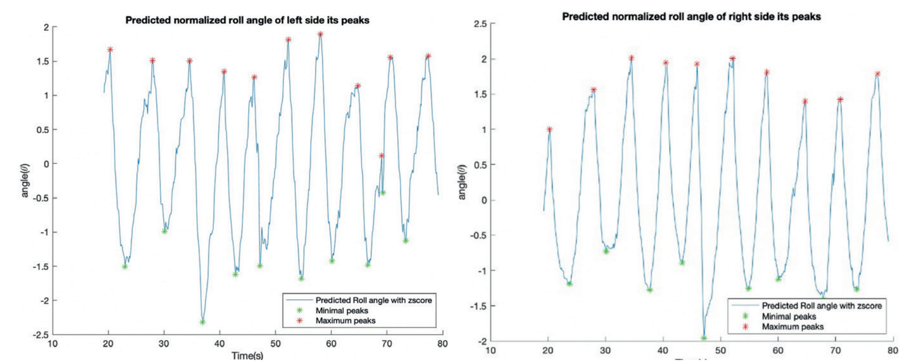

Fig. S2. Inertial sensor placed on left (left) and right (right)

TACHYPNEA PATTERN:

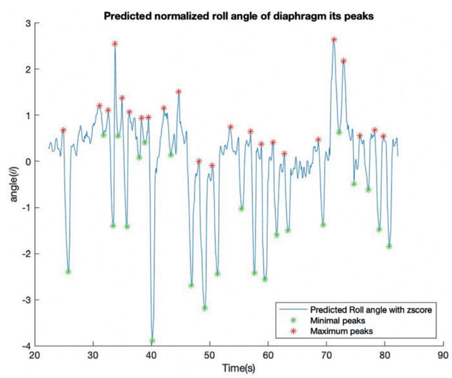

Fig. S3. Inertial sensor placed on diaphragm

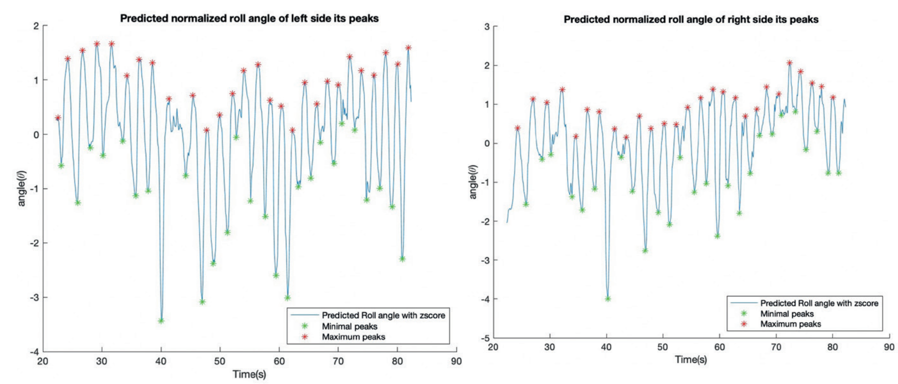

Fig. S4. Inertial sensor placed on left (left) and right (right)

HOLD-RESPIRATION PATTERN

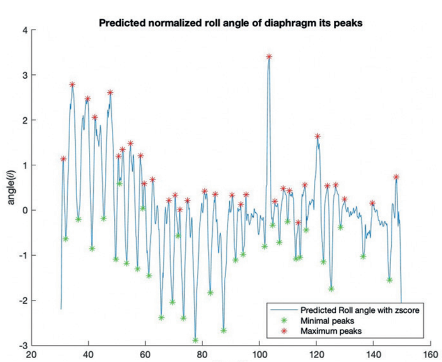

Fig. S5. Inertial sensor placed on diaphragm

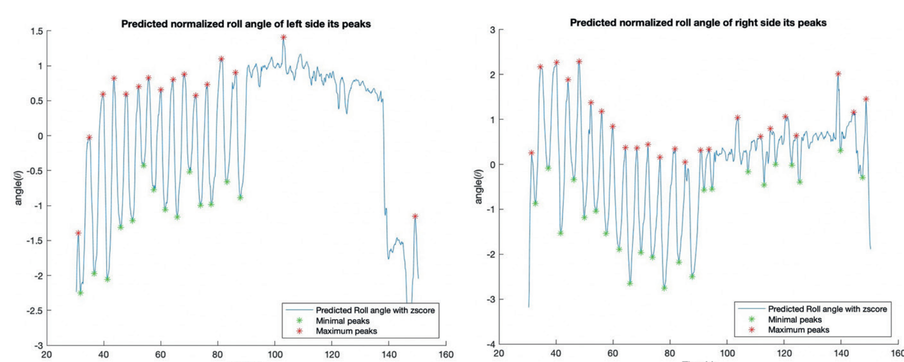

Fig. S6. Inertial sensor placed on left (left) and right (right)

An ontology-based approach to support the knowledge management of software quality standards

Una propuesta basada en ontologías para apoyar la gestión del conocimiento de estándares de calidad de software

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***Abstract* — Nowadays, the quality of software systems is crucial for companies to provide high-quality services and products. However, a wide number of software projects still fail. To increase the success probability of projects, it is suitable to adopting software quality standards to guide the process. However, standards are commonly described by means of natural language making difficult its analysis. For example, it is not easy to choose the most suitable standard according to the characteristics of a project. Furthermore, the usage of natural language hinders the automatic detection of inconsistencies and ambiguities. On the other hand, ontologies are an artificial intelligence technique that has been successfully used to represent and analyze knowledge in numerous domains because its capacity to enable the automatic validation and consistency checking of the represented information. This paper aims to present an ontology-based approach to describe and analyze software quality standards. Since this ontology can represent the knowledge of several standards, a reasoner may automatically validate the information and infer new knowledge. This ontology might support the reduction of conceptual ambiguity of standards descriptions and improve its understanding.**

***Keywords* - quality standards; ontology; software; knowledge representation.**

***Resumen* — En la actualidad la calidad de los sistemas de software es crucial para que las empresas brinden servicios y productos de alta calidad. Sin embargo, un número importante de proyectos de software aún fallan. Para aumentar la probabilidad de éxito de los proyectos, es conveniente adoptar estándares de calidad de software que guíen el proceso. Sin embargo, los estándares se describen comúnmente por medio del lenguaje natural, lo que dificulta su análisis. Por ejemplo, no es fácil elegir el estándar más adecuado según las características de un proyecto. Además, el uso del lenguaje natural dificulta la detección automática de inconsistencias y ambigüedades. Por otro lado, las ontologías son una técnica de inteligencia artificial que se ha utilizado con éxito para representar y analizar el conocimiento en numerosos dominios debido a su capacidad para permitir la validación automática y la comprobación de la consistencia de la información representada. Este artículo tiene como objetivo describir una propuesta basada en ontologías para describir y analizar estándares de calidad del software. Dado que esta ontología puede representar el conocimiento de varios estándares, un razonador puede validar automáticamente la información e inferir nuevo conocimiento. Esta ontología podría apoyar en la reducción de la ambigüedad conceptual de las descripciones de estándares y mejorar su comprensión.**

***Palabras Clave* - estándares de calidad; ontología; software; representación del conocimiento.**

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I. INTRODUCTION

NOWADAYS, the number and complexity of software projects are growing more and more. However, it is noteworthy the number of projects that ar e not successful in terms of time, cost, and software quality. For example, according to the Chaos report in 2020, only 35% of projects were fully successful in terms of time and budget [1]. The adoption of good practices to carry out the software development process is a suitable alternative to increase the success probability. The good practices include the application of guidelines to carry out each stage of the software lifecycle as well as the application of international standards. These standards are internationally agreed by experts and are promoted by important organizations in the software industry. For example, the International Organization for Standardization (ISO), together with the International Electrotechnical Commission (IEC), provide some of the most important international standards. Likewise, the Software Engineering Institute (SEI) [2] and the Institute of Electrical and Electrotonic Engineering (IEEE) are two relevant organizations in the definition of international standards. A standard is a document established by an authority, custom, or general consent as a model or an example [3].

In spite of the positive impact of adopting standards, it is not a straightforward task. The standards are usually described in complex and large documents represented by natural language. Hence, the analysis of these documents is a complex task, especially if several standards are being analyzed. For example, it is possible to find different terms for the same concept or the same term for different concepts for different standards. These issues hinder the right application of the standards; for instance, it is not easy to choose the proper standard for a project according to its characteristics.

On the other hand, applying formal models to partially describe the knowledge of the standards might be an alternative to tackle the aforementioned issues. In that sense, the ontologies, represented by means of Ontology Web Language (OWL), are an artificial intelligence technique that has been used to represent and analyze knowledge in different domains [4-6]. The ontologies allow to represent the knowledge of a domain and support the reasoning tasks on the concepts [7]. They also contribute to a shared understanding among different agents, such as people and software systems [8].

The main problem addressed by this research is related to how to increase the quality of descriptions about quality standards and consequently increase their accuracy and understandability as well as to reduce the time needed to get relevant information. To deal with this problem and considering the advantages of ontologies, this paper aims to describe an ontology-based approach to representing and analyzing the knowledge related to software development standards. The ontology was elaborated following a sound methodology that includes seven stages. The execution of these stages allowed us to define the classes, properties, and individuals of our ontology. In this process we analyzed a set of international standards to create a general ontology that could be used to represent information from different sources. Since several standards will be represented by means of the same ontology, a reasoner could analyze it to automatically validate the information and infer new knowledge. To demonstrate the applicability of the ontology, we populated it with knowledge of two standards. This ontology is a feasible tool to support the unification, integration, and reduction of conceptual ambiguity of software standards descriptions. Therefore, it might contribute to improving the accuracy of these descriptions and consequently make it easier the understanding of software standards.

Besides, once this ontology is populated it may be considered a knowledge base. Hence, it could be queried to carry out intelligent searches according to the user's needs. For example, a user could query this knowledge base to know the most suitable standard taking into account the characteristics of his project. Furthermore, since the knowledge will be explicitly described, the adoption of this type of approach could contribute to avoid misunderstanding and enhance the commutation of all stakeholders. On the other hand, with the systematic application of this ontology it will be possible to gather information regarding the results of applying a specific standard in a project. Therefore, the users could analyze all this information and use it to make decisions.

The structure of the paper is as follows: section 2 briefly analyzes some elements about standards and ontologies. In section 3 the main components of our ontology are described and a case study to demonstrate the applicability of our approach is presented. Finally, conclusions and future work are introduced.

II. MATERIALS AND METHODS

To perform this research, several research methods were used. First of all, a survey was conducted to identify the most common quality standards in the domain of software development. Based on the results of this survey, we carried out a documentary analysis to know the main components of the most adopted standards. These results were used as an insight to create the ontology that is presented in this article. To validate the ontology, a case study was implemented. For this case study, we used ontology to represent the knowledge of several quality standards. This case study demonstrated the applicability of the proposal to represent knowledge and to make easier the analysis of quality standards.

In addition to these research methods, we describe in this section the particular methodology, language and tool that were adopted to create the ontology. These elements are key to ensure the quality of the ontology from early stages of the development process.

A. Survey to identify Standards for the software development process

A survey was conducted to identify the most representative standards. In this study, software developers of two software development companies participated. We asked the participants to mention the best standards for the software development process. ISO and Capacity Maturity Model Integrated (CMMI) got the best results. Based on these results, we carried out an analysis of these two standards to know their main components. These results were used to create the ontology that will be described above in this paper.

Software quality standards include specifications to ensure that the outputs of the software development process meet business expectations. This guides the appropriate application of software engineering [9]. Hence, it plays a crucial role in managing and ensuring software quality. The standards focus either on the process or the product [10].

ISO 9001:2015 has been widely implemented for quality management around the world. It includes a set of principles to the right implementation of a system of quality management in organizations that develop software or provide services [11]. CMMI is based on Capacity Maturity Model (CMM). The aim of CMMI is to assess and enhance the maturity of the processes of software development. The Guide to the Project Management Body of Knowledge (PMBOK) provides guidelines for managing projects. PMBOK describes the projects lifecycle and their processes [3].

B. Documentary analysis

As Andrade et al defined, a Documentary analysis is a procedure which encompasses the identification, verification and consideration of documents which are related to the object investigated [12]. In our research, we are interested in considering documents which describe standards for the software development process. Since we previously conducted a survey to identify the most used standards for software development, we focused the analysis on those selected standards. Specifically, we used the normative documents of the respective standards.

This analysis allowed us to understand better the knowledge related to these standards. By means of this technique, the general structure of each standard was identified, as well as their main components. These results were an important insight to develop the ontology that is presented in this paper. Likewise, we used the results of this study to populate the ontology and evaluate its quality.

C. Case Study

To carry out the case study we followed the steps defined by Crowe et al [13]: *Defining the case; Selecting the cases; Collecting the data*; and *Analyzing, interpreting and reporting case studies*. In our research, we defined our cases as the descriptions of software quality standards that were specified by means of the ontology developed in this research. Our focus was on how a formal description of standards can contribute to improving the accuracy of these descriptions and, consequently, make it easier the understanding of software standards. Based on the results of the survey mentioned above, we focused our study on the standards CMMI, ISO and PMBOK.

Regarding the data collection, first of all, we used the official descriptions of these standards [2, 3, 11]. This collected information was used in the process of creating the ontology as well as to populate it. Finally, the step of analyzing the results was guided by a set of competence questions. We evaluated how the ontology was able to answer these questions. *Section 3. C* describes the main results of this case study.

D. Methodology and tools adopted to develop the Ontology

As was mentioned in the introduction, this paper aims to describe an ontology-based approach to representing and analyzing the knowledge related to software development standards. An ontology is a formal and explicit specification of a shared conceptualization [14]. It is composed of concepts, axioms, or inference rules that can be used to infer new knowledge. The ontologies contribute to detecting and removing ambiguities [15]. They are a tool to manage the knowledge of a specific domain, enhancing the understanding of the specifications and creating new knowledge.

A crucial step to ensure the quality of an ontology is the selection of the methodology that will guide the ontology development process. Likewise, it is relevant to select the right language and the tool to implement the ontology.

The development of our ontology was guided by the methodology proposed by Noy and McGuinness, which has been extensively adopted [16]. This methodology is one of the most used or cited for designing an ontology [17]. It includes the following steps: Determine the domain and scope of the ontology, consider reusing existing ontologies, list the relevant terms of the ontology, define the classes and the class hierarchy, define the properties (called relationships or slots) of the classes, define facets and/or restrictions on slots or relationships and finally define instances.

Web Ontology Language (OWL) is one of the most prominent languages to represent ontologies. OWL allows to describe concepts and relationships among them [18]. To create and edit the ontology we employed the tool Protégé because it is an open-source platform that has been used extensively to manage ontologies in OWL [19].

III. RESULTS AND DISCUSSION

A. Ontology to represent the knowledge of software quality standards

Following the steps of the methodology described in the previous section, an ontology to represent and analyze the knowledge of software standards was developed. Below the main results of the otology development process are analyzed.

Step 1. Define the domain and scope of the ontology.

The main goal of the ontology is to support the analysis of software standards. Its application will contribute to enhancing the understanding of a specific software standard as well as finding common concepts and terms among different standards. To assess the compliance of these objectives, the following competence questions (CQs) were defined:

CQ 1. What are the main components and subcomponents of a specific standard?
CQ 2. What goals and practices are satisfied for a company that reached a certain maturity level?
CQ 3. What process areas should be implemented in an organization to reach the next maturity level?
CQ 4. What companies have a level that is not according to the practices or goals that they accomplish?
CQ 5. What specifications are common in different standards?

CQ 1 is focused on the concepts that compose each standard. It has been used to represent information about CMMI_DEV version 1.3 and PMBOK 6[th] edition to illustrate the applicability of our approach. Hence, CQ 1 will be answered with specific information about these standards. CQ 2, CQ 3 and CQ 4 focus on the information that can be inferred in an organization that implements a standard, in this case, CMMI_DEV. CQ 5 will allow to know the concepts in a standard which have a correspondent concept in other standards.

Step 2. Consider reusing existing ontologies

Since we did not find ontologies in the English language, we do not reuse ontological resources from other ontologies.

Step 3: List the relevant terms of the ontology.

To identify relevant terms, we conducted a documentary analysis of several references that describe standards. Some relevant terms are Process, Area, Practice, Goal, Tool, Level, Input, Output, among others.

Step 4: Define the classes and the class hierarchy

In this stage, we analyzed the identified terms in the previous stage to decide which of them will be considered as classes in ontology. After this analysis, 48 classes were identified. The classes **Standard** and **Part** are two of the most significant classes in the ontological model. Each of these classes subsumes other classes to characterize the individuals that compose it and thus provide analysis of interest. Fig. 1 depicts the hierarchy of the classes **Part** and **Standard**. We defined that a **Standard** is composed of a set of **Main_Components**, and each **Main_Component** is composed of a set of **Sub_Components**. The types of **Main_Component** and **Subcomponent** depend on the Standard. For example, **Knowledge_Are**a and **Process_Area** are the main components of the standards PMBOK_Edition_7th and CMMI_Dev_1.3, respectively. Whereas a **Knowledge_Area** includes a set of **Processes**, a **Process_Area** is composed of **Goals** and **Practices**. On the other hand, we included classes to classify a Standard according to its purpose. Thus, we have the classes **Standard_Focused_On_Process**, **Standard_Focused_On_Product** and S**tandard_Focused_On_Product&Process**.

Fig. 1. Hierarchy of the classes **Part** and **Standard**.

Step 5: Define the properties

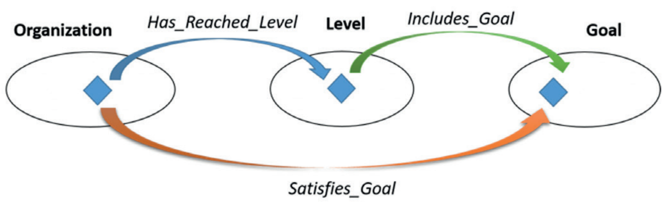
The properties are the other key component in an ontology. OWL defines two types of properties, *object* and *data properties*. An object property allows representing a relationship between two individuals. In OWL, to define the classes that can use a property, the domain and range of the property should be defined. For example, an individual of the class **Standard** *Has_Main_Part* individuals of the class **Part**. For this example, the property *Has_Main_Part* has the classes **Standard** and **Part** as domain and range, respectively. Table 1 shows some of the object properties for the classes **Standard**, **Process_Area**, **Goal**, and **Organization**. In total, the ontology includes 67 object properties. Furthermore, the expressive richness of OWL allows us to specify an inverse for each property. For example, the property *Supports_Generic_Practice* has the inverse property *Is_Supported_By*. If **A** *Supports_Generic_Practice* **P**, then a reasoner will infer that **P** *Is_Supported_By* **A**.

TABLE I
A SAMPLE OF OBJECT PROPERTIES

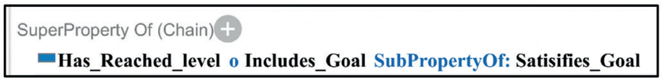
Domain	**Property**	**Range**
Standard	*Has_Part*	
Has_Main_Component	*Part*	
Standard	*Defines_Level*	Level
Process_Area	*Is_Part_Of*	Standard
Process_Area	*Has_Specific_Goals*	Goal
Process_Area	*Is_Associated_To_Level*	Level
Process_Area	*Supports_Generic_Practice*	Generic_Practice
Specific_Goal	*Has_Specific_Practice*	Specific_Practice
Organization	*Has_Reached_Level*	Level
Organization	*Satisfies_Goal*	Goal
Organization	*Satisfies*	Practice
Organization	*Must_Implent_Area*	Process_Area

In OWL, it is possible to specify the characteristics of an object property. For example, to answer CQ 5 we created the object property *Is_Compatible_With* to relate the elements of different standards that are similar. This property was defined as symmetric, which means that if f A *Is_Compatible_With* B then the reasoner infers that B *Is_Compatible_With* A.

The expressive richness of OWL allows to represent not only direct relationships between individuals; it is possible represent more complex relationships by means of property chains. For example, if a company has adopted the **Standard** CMMI_DEV and has reached the maturity level 4 (*Quantitatively managed*), we would like to know the goals and practices that this company satisfies. Fig. 2 a) shows a representation of the relationship among the classes **Organization**, **Level**, and **Goal**. Whereas Fig. 2 b) shows how this relationship was expressed by means of a property chain (*Satisfies_Goal*). A similar property chain was defined to represent the relationship between **Organization** and **Practice** by means of the object property *Satisfies_Practice*.



(a)



(b)

Fig. 2. (a) Example of relationships among classes; (b) Example of property chain *Satisfies_Goal*.

On the other hand, data properties allow to define some basic attributes for the classes. For example, Table II shows some of the data properties identified for the classes **Standard** and **Organization**. Similarly, to object properties, data properties have domain and range, but in this case, the range is a data type, for example, String, Integer, Date, etc.

TABLE II
A SAMPLE OF DATA PROPERTIES

Domain	Property	Range
Standard Organization	*Has_Name* *Has_Description*	String
Standard	*Has_Publication_Date* *Has_Expiration_Date*	Date
Standard	*Has_Version*	Standard
Organization	*Must_Implent_Area*	Process_Area

Step 6: Define facets and/or restrictions

OWL allows specifying universal and existential restrictions. For example, Fig. 3 shows the existential restriction to express that a **Standard** *Has_Main_Component* some instances of the class **Main_Component**. It means that each Standard should have at least one **Main_Component**. Whereas Fig. 3 also depicts a universal restriction (identified for the word *only*). With this statement, if a Standard S is related to an individual X by means of the property *Has_Main_Component*, the reasoner will classify **X** as a **Main_Component**.

Fig. 3. Example of existential and universal restrictions.

On the other hand, OWL allows defining sets of necessary and sufficient conditions for a specific class. The classes with this type of conditions are named defined classes. The main advantage of this type of classes is that a reasoner can automatically infer the individuals that belong to them. To take advantage of these potentialities, several defined classes were created. For example, we created the class **Organization_Level_4** for the organizations that adopted the **Standard** CMMI_DEV and have reached the maturity level 4 (*Quantitatively managed*). Fig. 4 shows this specification.

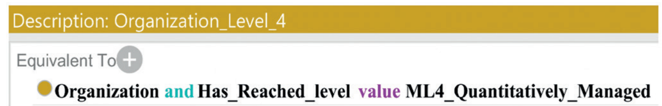


Fig. 4. Example of a defined class.

We used Semantic Web Rule Language (SWRL) to specify more complex relations. For example, to answer CQ 5 we created the Class **Company_With_Problems** and specified Rule 1 to infer the companies that belong to this class.

Organization(?o) ^ Satisifies_Goal(?o, ?g) ^ Not_Satisfies_Goal(?o, ?g) -> Company_With_Proplems(?o)

Rule 1. Rule in SWRL to detect companies with problems

Step 7. Define instances

In this step, instances of each class are defined, and the necessary axioms to link them are established. A case study with results of this step is explained in the next section. Furthermore, this case study demonstrates the applicability and usefulness of this ontology.

B. Ontology validation

To validate the ontology, we checked that *a) it meets the specifications of a formal-logical system*; and *b) it satisfies the requirements for which it was created*. A reasoner is used to verify that the specifications as a formal-logical system are fulfilled. In this case, we used the reasoner Pellet [20], which confirmed that the ontology is consistent. The ontology evaluation is an iterative and progressive process. Throughout the life cycle of ontology development, we continually use the reasoner to verify the consistency of the ontology.

In addition, the last version of the ontology was tested by using OntOlogy Pitfall Scanner (OOPS!) [21]. After four iterations, all the problems detected by OOPS were fixed. This evaluation helped to detect and correct some pitfalls in our ontology.

We carried out a case study to demonstrate that the ontology satisfies the requirements for which it was created. In this case study, we verified that all competency questions were answered correctly by the ontology. The case study described in the next section also illustrates the usefulness and applicability of our ontology.

C. Case Study

A case study is presented below to demonstrate the applicability and usefulness of the ontology. As mentioned before, we presented in our ontology the information about the standard

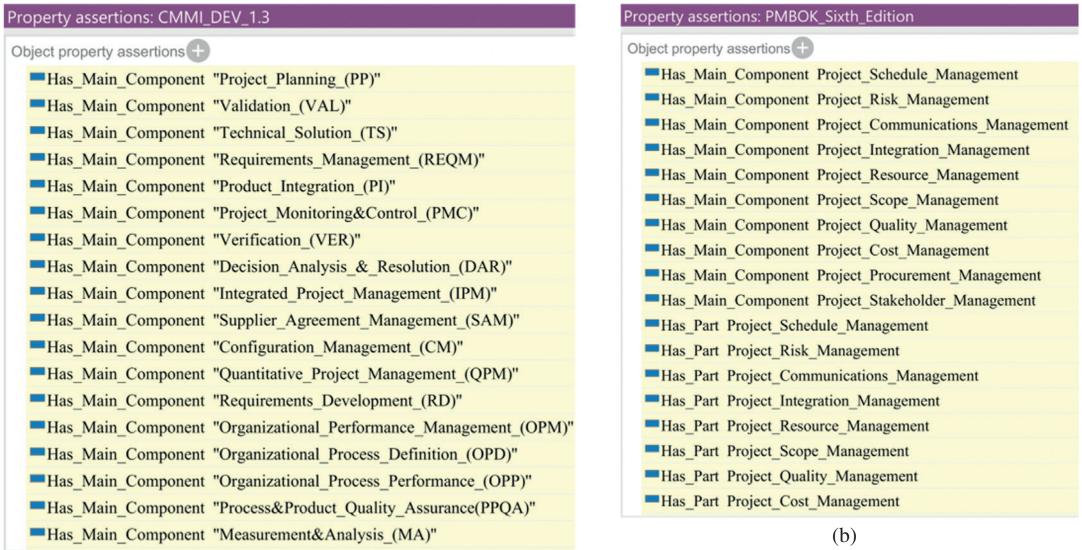


Fig. 5. Inference of the main components of (a) CMMI_Dev_3.1; and (b) PMBOK_6th_Edition.

CMMI_Dev version 3.1 and the guide PMBOK 6th edition. In spite of the fact that PMBOK is not a standard, it has been extensively adopted to guide the development of different types of projects [22]. We created the individuals PMBOK_6th_Edition and CMMI_Dev_3.1 as instances of the class **Standard**. Then the respective axioms to represent the particular information of each standard were created. For example, the main components of *PMBOK_6th_Edition* are instances of the class **Knowledge_Area**, whiles for *CMMI_Dev_3.1* are instances of the class **Process_Area**. To answer CQ 1, Fig. 5 shows the main components of the Standards *CMMI_Dev_3.1* and *PMBOK_6th_Edition*. Considering these statements, the reasoner will classify the instances of these two classes as **Main_Component**.

In addition to know the main components of a standard, it is useful to know about the other subcomponents. For example, in *PMBOK_6th_Edition*, each process belongs to a group of processes. Hence, it is interesting to know the list of processes that belong to a specific group of processes. Fig. 6 shows the processes that belong to the **Group_of_Processes** *Monitoring&Controlling_Process_Group*.

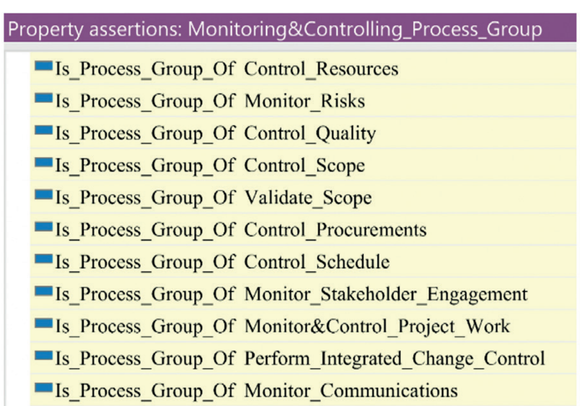


Fig. 6. Processes that belong to the **Group_of_Processes** *Monitoring&Controlling_Process_Group*

Since we defined a set of property chains, it is possible to get information about individuals who do not have direct relationships as well. For example, it is possible to know the inputs or outputs of a specific **Group_Of_Process** or a **Knowledge_Area**. Fig. 7 a) shows the inputs/outputs of the **Knowledge_Are**a *Poject_Quality_Management*, and Fig. 7 b) shows the inputs/outputs of the **Group_Of_Process** *Executing_Process_Group*. Likewise, taking into account the specifications of the ontology, it is possible to know the list of processes where certain work document is used. These examples illustrate the usefulness of the expressive richness of OWL. The application of this ontology could speed up the analysis of the standards.

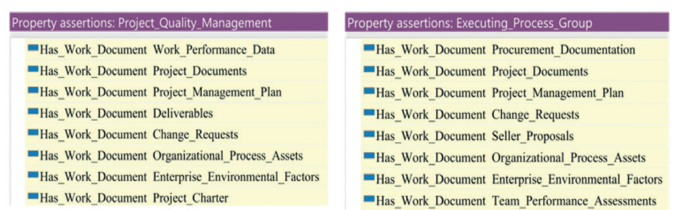


Fig. 7. List of inputs/outputs of (a) the Knowledge_Area Poject_Quality_Management; and (b) the Group_Of_Process Executing_Process_Group.

To exemplify how the ontology is able to answer CQ 2 and CQ 3, we added the individuals *Company_Soft&Serv_For_Health* and *Software_Company_Multi_System* as instances of the class **Organization**. For Software_Company_Multi_System, we added the axiom to define that this company reached maturity level 5 (*ML5_Optimizing* in the ontology). Fig. 8 a) shows that the reasoner inferred the goals and practices that this company satisfies. For *Company_Soft&Serv_For_Health*, we added the axiom to define that reached the level 4 (*ML4_Quantitatively_Managed* in the ontology). Fig. 8 b) shows that the reasoner inferred that this company must implement the process areas *Organizational_Performance_Management_(OPM)* and

Causal_Analysis_&_Resolution_(CAR) to reach the next level. The answers to CQ 2 and CQ 3 may be a useful insight to decisions according to a company's level.

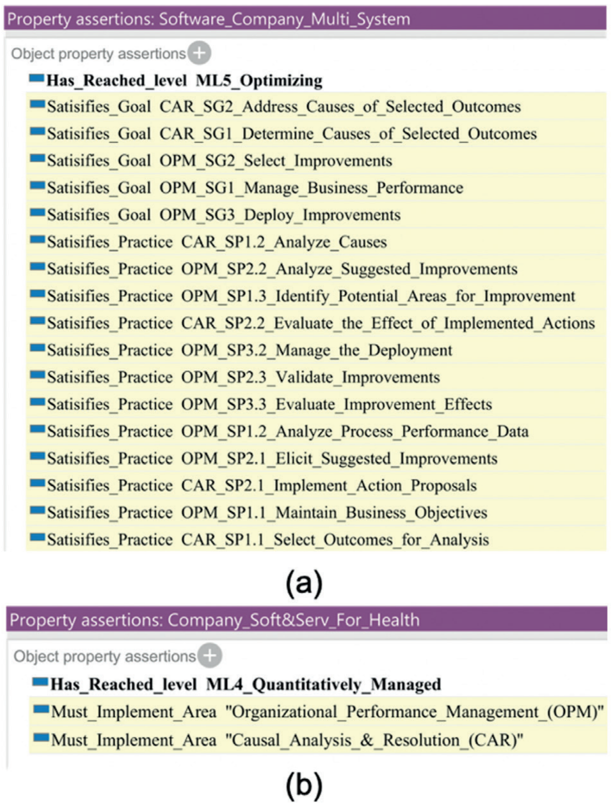


Fig. 8. (a) Inference of the goals and practices that a company satisfies; (b) Inference of the process areas that a company should implement.

To answer CQ 4, we specified that the company *Software_Company_Multi_System* does not satisfy the goal *OPM_SG1_Manage_Business_Performance*, which is a goal that must satisfy the companies that reached level 5. Since we previously defined that this company reached level 5, the reasoner classified this company as *Company_With_Problems*, as Fig. 9 shows. This type of inference is useful to detect inconsistencies due to either human mistakes adding to the information or real problems with the companies that are not implementing goals or practices that they should implement. Specifically, this type of analysis is common after a company has been assessed.

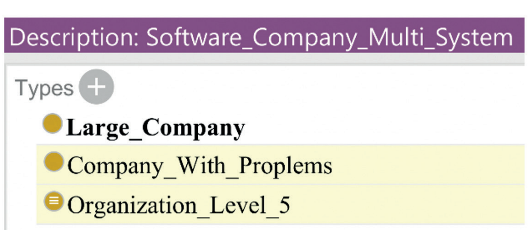


Fig. 9. Automatic classification of a *Company_With_Problems*

To illustrate how CQ 5 is answered, we created in the ontology the class **Component_Multi_Standard**. Furthermore, we defined the necessary and sufficient conditions to automatically classify the instances of this class (Fig. 10 a). Fig. 10 b) shows that the reasoner identified a group of individuals that belong to the class **Component_Multi_Standard**. For example, as Fig. 10 d) shows, *Project_Quality_Management* is Compatible_With *Process&Product_Quality_Assurance(PPQA)*. Since the property *Compatible_With* was defined as symmetric, the reasoner inferred that *Process&Product_Quality_Assurance(PPQA)* is *Compatible_With Project_Quality_Management* as Fig. 10 c) shows.

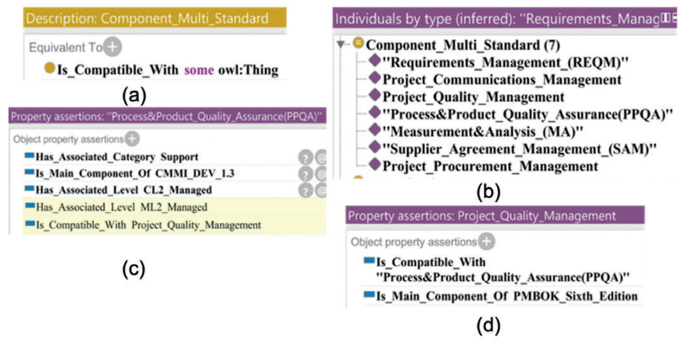


Fig. 10. (a) Definition of the class *Component_Multi_Standard*; (b) Inference of instances of the class *Component_Multi_Standard*; (c) Example of *Component_Multi_Standard*; (d)Example of *Component_Multi_Standard*

IV. CONCUSSIONS AND FUTURE WORK

This work presented an ontological approach to representing and analyzing the knowledge of different standards. We described how the expressive richness of OWL was exploited to represent a wide diversity of relationships. The ontology includes specifications to represent not only the specific information of a standard, but it is possible to relate this information with the data of the organizations and identify common concepts among different standards. We demonstrated by means of a case study that this approach could support the analysis of different standards. This ontological model could be a useful tool to speed up the adoption of a standard. Furthermore, the ontology might be used as a valuable material to train company personal staff. On the other hand, since OWL is a formal language, this ontology allows detecting inconsistencies or ambiguities. The systematic application of this approach will help to populate the ontology. Hence this ontology could represent a reference knowledge base.

Our future work will be focused on the extension of the ontology to represent the information of other standards and identify the common concepts among different standards. Furthermore, we are designing an experiment to assess the impact of this approach to improve the analysis of these standards in terms of time and quality of the analysis. In addition, we are examining approaches to automatically extract information from documents in natural language. With the application of this type of approach, the population of the ontology could be easier. Finally, since we expect to populate this ontology with the information of a significant number of standards and companies, we are exploring alternatives to address its scalability.

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