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Addressing Simplicity, Dexterity and Usability of Compact, Multi-Degree-of-Freedom Mechatronic Devices

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***Abstract*— Many modern multi-degree-of-freedom mechatronic devices are characterized by considerable and often severe size and weight constraints, and it is therefore desirable to address the design of such devices in a systematic and effective manner. The design evaluation and improvement technique being investigated in this work revolves around three desirable yet often conflicting attributes of devices of this type, being simplicity, dexterity and usability. Detailed qualitative definitions of these terms are proposed. Furthermore, a method that quantifies these design attributes in an arbitrary device of this type is presented. This method is aimed at providing objective measures of the strengths and weaknesses of the design, and the mathematical tool can assist designers and engineers in evaluating, comparing and improving device designs. Towards the end of the paper the methodology is applied to a case study to augment the design process of a minimal anthropomorphic robot hand.**

I. INTRODUCTION

Throughout time, individuals have sought the possibility of shifting the burden of manual work from the responsible person to a mechanised device. This ambition fueled the development of numerous mechanisms that are capable of accomplishing tasks more efficiently and effectively than the human counterpart.

The drastic refinements achieved in technology throughout the past few decades prompted the development of mechatronic devices that must adhere to strict design requirements. In many cases, these types of devices are expected to execute multiple motions whilst following strict weight and space limitations. In fact, this can be noted from the emergence of highly-dexterous grippers and tools aimed for the manufacturing industry [1], advanced domestic devices [2], advanced medical manipulation tools [3], and space exploration devices [4], amongst others. As these devices must satisfy a distinct set of design requirements, as compared to traditional devices, these are herein referred to as *compact, multi-degree-of-freedom* (CMDOF) devices.

Despite the rapid developments achieved in this field, it is likely that a number of CMDOF devices must sacrifice their mechanical simplicity to meet the expected functional requirements. As a consequence, the complexity could result in the device being unfeasible to develop and/or unusable to the typical user (i.e. difficult to operate). On the other hand, if the design of the device is highly simplified, the device may not attain the expected functional requirements. The operability of the device may also be negatively influenced, depending on the extent of design simplification.

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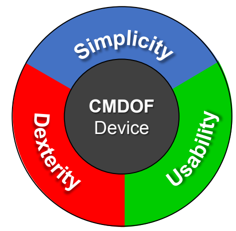


Fig. 1: Three main design attributes of a CMDOF device.

In light of this, three generic, high level *design attributes* which ideally should be maintained at a high extent for an effective CMDOF device are proposed, being: ***simplicity***, ***dexterity*** and ***usability*** (represented in Fig. 1). Maximizing the three attributes simultaneously is perhaps a difficult task to attain due to their apparent conflicting nature. Hence, it is important to achieve a sensible trade-off between the attributes for an effective design.

The selected attributes aim at covering a wide range of critical design aspects necessary for an effective device. In brief, *simplicity* refers to the device features which result in a straightforward design, enabling it to be more easily produced, less expensive, and more reliable in the long run. *Dexterity* is usually associated with the abilities of a hand. However, in this work the definition is extended to refer to the motion related abilities of CMDOF mechatronic devices. Lastly, *usability* refers to the qualities enabling the device to be easily operated by the user. A device that excels in all the three attributes is likely to possess a highly effective design.

Determining the extent of these three attributes as exhibited by a specific device can provide a very good indication of the effectiveness of its design. In this work, qualitative and quantitative definitions of the three attributes based in large part on definitions presented in literature are proposed. Being aware of the factors that influence the desirable attributes of the design is likely to stimulate design improvements. In fact, the derived definitions are exploited in this work in order to improve the design of a previously developed robot hand at the University of Malta. A brief comparison between the design attributes of the previous and the new robot hand is made at the end of this work.

II. DESCRIPTION OF THE ATTRIBUTES

A. Introduction

Several attempts have been made in literature to establish the fundamental definitions of simplicity, dexterity and usability. It was observed that in general these attempts addressed only one particular attribute at a time. As a consequence, this promoted design improvements to be enhanced along one particular dimension only, often without regard to the other design attributes.

In this section, qualitative definitions of the three attributes, primarily based on definitions from literature, are presented. As each attribute is highly abstract and incorporates a wide array of design aspects, a systematic procedure is formulated to ensure that each attribute is equally prioritized. The ***main constituents*** for each attribute are identified, basically representing the fundamental elements which must be present for the attribute to exist.

Therefore, the *main constituents* of the *simplicity* attribute are identified as the ***components*** of the device, as design simplifications are primarily attained by appropriate modifications in the design of the components constituting the device. The *main constituents* of the *dexterity* attribute are identified as the ***functions*** of the device, since enhancing the capability of the device functions is likely to improve the dexterity of the device. Finally, the *main constituents* of the usability attribute have been identified to be the ***interactions*** between the device and the user.

The *main constituents* have been sub-divided into *classes*, and the generic individual factors pertaining to all the classes under each attribute are then identified, referred to as the ***primary factors***. Each *primary factor* is then further broken down into the corresponding ***secondary factors***. All these factors are identified in the remainder of Section II. This general hierarchy of factors is shown in Fig. 2. Once the individual factors have been defined, a formal definition for each attribute is then formulated.

B. Simplicity

The term *simplicity* (here given the symbol S) has been characterized in different ways in literature, either by referring to a single concept [5], [6], or multiple concepts [7], [8], related to the components of the device. The components of CMDOF devices can be classified under four *classes* being: *actuators* ($S1$), *sensors* ($S2$), *joints* ($S3$) and *kinematic members* ($S4$), and by enhancing the factors below for each class, it is likely to promote a simplified design. In this work, the definitions representing similar key ideas are classified under *primary* and *secondary factors* accordingly, and are formally proposed below. Four *primary factors* are defined ($Si.1$, $Si.2$, $Si.3$, and $Si.4$, where i refers to the particular class of components to which the factor is being applied), and two further *secondary factors* (e.g. $Si.1.a$ and $Si.1.b$) are defined for each primary factor. The secondary factors are described below and for better comprehension, an example for each is visually illustrated in Table I.

$Si.1$. Component plainness

Absence of design features ($Si.1.a$)***:*** Design features refer to geometrical features that are introduced in order to alter the raw form of the component under consideration (e.g. extrusion, holes). Reducing the design features present in the component is likely to promote a simpler design.

Absence of auxiliary components ($Si.1.b$)***:*** Auxiliary components refer to parts which are introduced in order to support the main component under consideration and/or are necessary for the full functionality of the component (e.g. bolts, mounting brackets). Reducing the amount of auxiliary components implies less parts require to be fabricated and/or to be handled, and hence it is likely to simplify the design.

$Si.2$. Component similarities

Compatible interfaces ($Si.2.a$)***:*** This refers to the design features which permit components to be coupled together. Components sharing common coupling interfaces promote identical design features and a modular design (e.g. threaded connection, flange coupling).

Physical similarities ($Si.2.b$)***:*** Components sharing similar physical properties are likely to reduce the variations in the design, hence promoting simpler components (e.g. same dimensions and material).

$Si.3$. Component relationships

Dependency ($Si.3.a$)***:*** A component that depends on other components must follow the design constraints imposed by the supporting components. Reducing the number of dependent components is likely to simplify the design (see Table I, gripper (A) mounted on articulated structure (B), vs. gripper (A) mounted on a single component (B)).

Responsibility ($Si.3.b$)***:*** A component that must cater for other components is likely to have its design also constrained to support the associated components (see Table I, base of structure (A) supporting articulated structure (B), vs. base component (A) supporting end effector (B) only).

$Si.4$. Component compactness

Lightness ($Si.4.a$)***:*** A light component is likely to ease the weight limitations on other components, which is a critical characteristic in CMDOF devices.

Smallness ($Si.4.b$)***:*** Similar to the previous definition, a smaller component is likely to ease the size limitations on the other components.

By considering the above derived definitions, a simple CMDOF design can be defined as one with an *effectively reduced number of components, with minimal features and minimal design variations incorporated in a compact design whilst imposing the least possible amount of design constraints, without compromising unacceptably the functionality of the device.*

C. Dexterity

A great deal of the *dexterity* (D) definitions in the literature concern the skills and/or abilities of the human hand or of artificial anthropomorphic devices [9], [10]. Nonetheless, the important key points that are in general applicable to CMDOF devices are derived in this work. These are formulated as primary and secondary factors below. Similar to the previous attribute, an example for each definition is visually illustrated in Table II.

As the functions are the main constituents of the dexterity attribute, these may be classified under two classes, being: *local functions* (e.g. actuation of a single joint) and *global functions* (e.g. walking action of a humanoid robot),

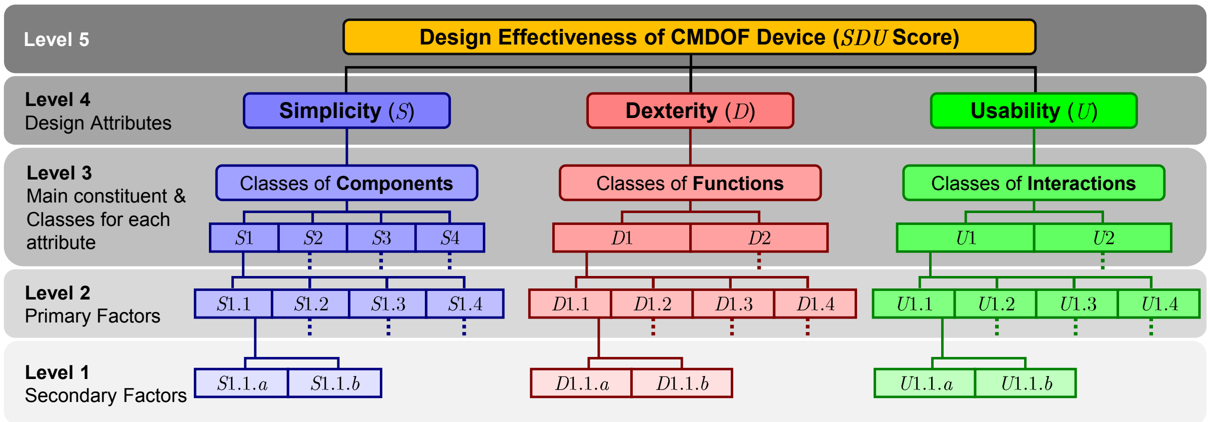
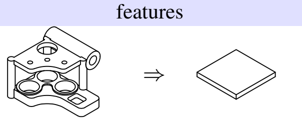
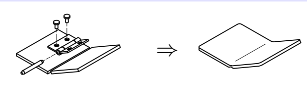
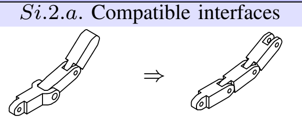
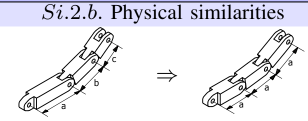
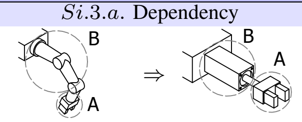
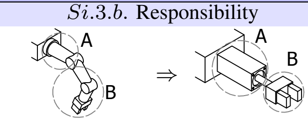
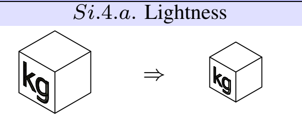
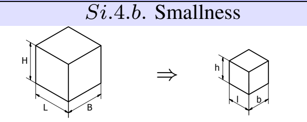


Fig. 2: General hierarchy of the factors pertaining to CMDOF design effectiveness.

TABLE I: Components with contrasting levels of simplicity.

SIMPLICITY (S)	
Main constituents: Components (**Four classes:** Actuators ($S1$), Sensors ($S2$), Joints ($S3$), Kinematic Members ($S4$))	
$Si.1.$ *Component Plainness*	
$Si.1.a.$ Absence of design features	$Si.1.b.$ Absence of auxiliary components
	
$Si.2.$ *Component Similarities*	
$Si.2.a.$ Compatible interfaces	$Si.2.b.$ Physical similarities
	
$Si.3.$ *Component Relationships*	
$Si.3.a.$ Dependency	$Si.3.b.$ Responsibility
	
$Si.4.$ *Component Compactness*	
$Si.4.a.$ Lightness	$Si.4.b.$ Smallness
	

represented by $D1$ and $D2$, respectively. Enhancing the following factors for each class is likely to enhance the dexterity of the device under consideration.

$Di.1.$ Function Motion

Translational motion **(**$Di.1.a$**):** A device that is capable of performing translational motion along the three dimensions (X, Y and Z) offers greater dexterity than devices with limited translational motion (e.g. XYZ cartesian robot vs. XY planar robot).

Rotational motion **(**$Di.1.b$**):** Similar to the previous definition, a device that is capable of attaining different rotational motions about the three axes (X, Y and Z) is likely to have enhanced dexterity (e.g. 3-D vs 1-D gyroscope).

$Di.2.$ Function Performance

Target attainment **(**$Di.2.a$**):** A device which achieves more easily the specified functional objectives is likely to be more dexterous (e.g. achieving the specified lifting capacity with a considerable safety factor).

Accuracy attainment **(**$Di.2.b$**):** Similar to the previous definition, a device that maintains better the specified accuracy values is likely to have greater levels of dexterity (e.g. achieving the specified positional accuracy more easily or more consistently).

$Di.3.$ Function Competence

Control over states **(**$Di.3.a$**):** This refers to the capability of the device of controlling the relevant states (e.g. position, velocity, force) of the device (e.g. position control using stepper motor, inclination control).

Feedback from states **(**$Di.3.b$**):** This refers to the capability of the device of retrieving feedback information from the states, usually for better control (e.g. improved position control using servo motor, tactile feedback).

$Di.4.$ Function Flexibility

Structural compliance **(**$Di.4.a$**):** Mechanisms which permit the device to absorb impact and conform with the external forces are likely to enhance the dexterity of the device (e.g. springs, elastic elements).

Control adaptivity **(**$Di.4.b$**):** Algorithms implemented in the controller of the device which are intended to mitigate the negative effects of external distrubances acting on the device (e.g. smoothed velocity profile, damped position).

The definition of dexterity with respect to a CMDOF device is proposed as *the ability of the device to achieve a wide array of movement or force-related functions by adapting part or all of its mechanisms effectively.*

D. Usability

The *usability* (U) aspects of mechanical devices have been discussed to a lower extent in literature [11], [12], compared to the two other attributes. Although the definitions presented below are primarily based on key points extracted from the literature, a significant amount of new insight is also used

TABLE II: Functions with contrasting levels of dexterity.

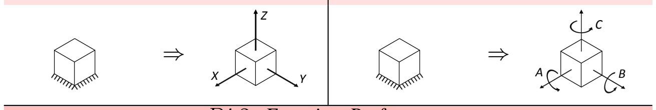
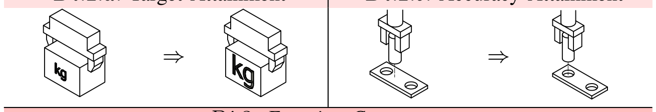
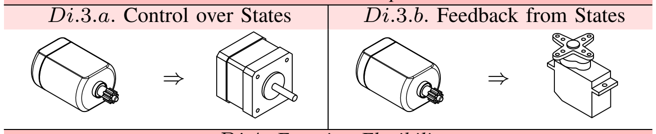
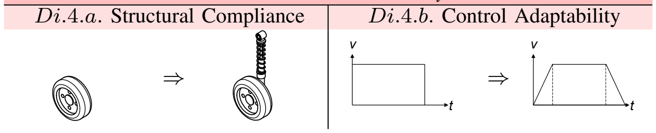
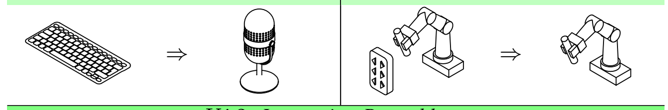
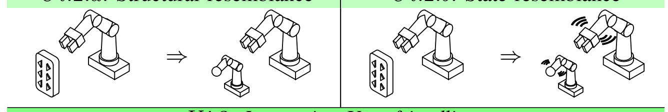
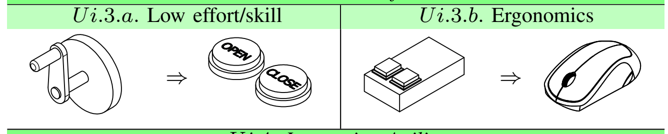
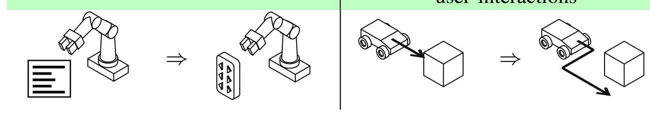
DEXTERITY *(D)*	
Main constituents: Functions (**Two classes:** Local functions ($D1$), Global functions ($D2$))	
Di.1. Function Motion	
$Di.1.a.$ Translational	$Di.1.b.$ Rotational
	
Di.2. Function Performance	
$Di.2.a.$ Target Attainment	$Di.2.b.$ Accuracy Attainment
	
Di.3. Function Competence	
$Di.3.a.$ Control over States	$Di.3.b.$ Feedback from States
	
Di.4. Function Flexibility	
$Di.4.a.$ Structural Compliance	$Di.4.b.$ Control Adaptability
	

TABLE III: Interactions with contrasting levels of usability.

USABILITY *(U)*	
Main constituents: Interactions (**Two classes:** Inputs ($U1$), Outputs ($U2$))	
Ui.1. Interaction Autonomy	
$Ui.1.a.$ Control abstraction	$Ui.1b.$ Device intervention
	
Ui.2. Interaction Resemblance	
$Ui.2.a.$ Structural resemblance	$Ui.2.b.$ State resemblance
	
Ui.3. Interaction User-friendliness	
$Ui.3.a.$ Low effort/skill	$Ui.3.b.$ Ergonomics
	
Ui.4. Interaction Agility	
$Ui.4.a.$ Operation immediateness	$Ui.4.b.$ Adjustment of user interactions
	

to complement the full definition of the usability attribute. As for the previous attribute, an example for each definition is visually illustrated in Table III. The *interactions*, being the main constituents of the usability attribute, are classified under two classes, being: *inputs* (e.g. teach pendent) and *outputs* (e.g. LCD screen), represented by $D1$ and $D2$, respectively. Improving the following factors in the device for each class is likely to promote a more usable device.

Ui.1. Interaction Autonomy

Control abstraction **(**$Ui.1.a$**):** A device that hides the complexity of the user-interface away from the user enhances the usability of the device, as the user is only concerned with the necessary inputs/outputs of the device (e.g. keyboard-input vs. voice-control).

Device intervention **(**$Ui.1.b$**):** A device that is able to take its own decisions is likely to be more usable as it permits the user to concentrate on more important functions of the device (e.g. teleoperation vs. self-controlled device).

Ui.2. Interaction Resemblance

Structural resemblance **(**$Ui.2.a$**):** This refers to the extent of similarities between the user-interface and the actual device under consideration (e.g. remote control box vs. input device resembling structure of device)

State resemblance **(**$Ui.2.b$**):** This refers to the extent of state similarities between the user-interface and the device (e.g. remote control box vs. haptic feedback input device)

Ui.3. Interaction User-friendliness

Low effort/skill **(**$Ui.3.a$**):** This describes the extent of effort or skill necessary to operate the device. A device requiring minimum effort/skill is likely to be more usable (e.g. pulley vs. buttons).

Ergonomics **(**$Ui.3.b$**):** This refers to the degree of comfort in using the device (e.g. geometry of input device).

Ui.4. Interaction Agility

Operation immediateness **(**$Ui.4.a$**):** This refers to the ability of the system to interact immediately with the actions of the user (e.g. programming vs. real-time operation).

Adjustment of user interactions **(**$Ui.4.b$**):** This refers to the ability of the system to modify the actions of the user in unexpected circumstances, such that for example it prevents any collisions/accidents.

From the above definitions, the usability attribute of a device is described as *the ability given to the user to impart minimum effort and resources to the device whilst successfully achieving the desired functions.*

III. QUANTIFICATION OF THE ATTRIBUTES

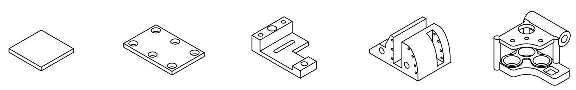
A generic mathematical procedure is proposed in this section to quantify objectively the extent of the attributes exhibited by a design, based on the definitions proposed earlier. Each secondary factor (hierarchical Level 1), primary factor (Level 2), class (Level 3), and attribute (Level 4), as well as the total SDU score (Level 5), is quantified to a normalized value that lies between 0 and 1. At the lowest level, each secondary factor is assigned a score according to the generic qualitative descriptions listed in Table IV. The *indicative factor percentage* column in this table can be used for added guidance in assigning the score, for example for factor $Si.1.a$ the ranges in this column refer to the percentage of the total component volume that is considered to be devoid of intricate design features (see the illustrative example in Table V). The scores are then summed upwards using successive applications of the normalized *square mean root* (SMR) function (e.g. [13]), defined by Eq. 1.

TABLE IV: Generic score indicator for secondary factors.

Score	**Qualitative** *Extent of factor*	**Quantitative** *Indicative Factor Percentage (%)*
1.00	Very high	$90 - 100$
0.75	High	$65 - 90$
0.50	Moderate	$35 - 65$
0.25	Low	$10 - 35$
0.00	Absent or very low	$0 - 10$

TABLE V: Scoring for *absence of design features* ($Si.1.a$).

Example components



Scores				
1.00	0.75	0.50	0.25	0.00

$$y_{j+1} = \left(\frac{\sum_{i=1}^{n_j} \sqrt{x_{i,j}}}{n_j} \right)^2 \quad (1)$$

where $y_{j+1}$is the partial summed score at level $(j+1)$, n_j is the number of elements to be summed at this particular branch of the hierarchical tree at Level j, and $x_{i,j}$ is the numerical value of each of these elements. The SMR function was chosen in order to penalize unevenly distributed scores. An additional factor is invoked to each element of Level 3 (i.e. to each class score), in order to penalize classes that incorporate a large number of physical subcomponents (simplicity branch), and/or a small number of functions (dexterity branch) and/or of interaction methods (usability branch), relative to the other classes within the group.

The final step in the calculation of the SDU score for a CMDOF device is therefore give by Eq. 2

$$SDU = \frac{(\sqrt{S} + \sqrt{D} + \sqrt{U})^2}{9} \quad (2)$$

where SDU represents the overall design effectiveness score.

The proposed *indicative factor percentage* is intended to increase the objectivity of the scores. However, future work is aimed at improving further the quantification techniques (applicable to any CMDOF devices), in order to increase further the objectivity.

IV. CASE STUDY: MINIMAL ANTHROPOMORPHIC ROBOT HAND

A. Introduction

As a case study, the derived factors are exploited to develop a minimal anthropomorphic robot hand that focusses on attaining an improved SDU score over a previously developed robot hand, the University of Malta minimal anthropomorphic robot (*UM-MAR Hand I*) [14]. The successor hand design will be referred to as *UM-MAR Hand II* [15] hereinafter. Although the presented work focusses on augmenting the design of a robot hand, the design characteristics of other CMDOF devices (uneven terrain vehicles and domestic cleaning devices) have also been assessed successfully using the same SDU method, hence demonstrating the broad applicability of the framework.

B. Earlier Version of Robot Hand: UM-MAR Hand I

The distinguishing feature of the *UM-MAR Hand I* is its minimal kinematic configuration, consisting only of two fingers and a thumb (Fig. 3a), resulting in a simplified mechanical architecture.

The kinematic configuration, empirically derived from a set of manual dexterity tests [16], resulted in a kinematic structure with 10 DOFs (8 of which are independently actuated). The robot hand was mainly based on an endoskeletal structure, to promote a compact design. The actuation system consisted of eight electric linear actuators, located in the forearm of the device. A series of tendon cables were used to transmit the forces produced by the actuators to the articulated hand structure. The robot hand could be controlled by the user in two different modes, either by a set of rotary potentiometers or via a glove-input device.

The robot hand design resulted in simplicity, dexterity and usability scores of 0.70, 0.27 and 0.52, respectively, and an overall SDU score of 0.49. The relatively high simplicity and usability scores of the device were attained at the cost of dexterity. Although the robot hand was able to perform most of the principal grasps outlined by Cutkosky [17], other important factors pertaining to the dexterity were not prioritized during the development of the device. The low score is mainly attributed to the low force exertion at the fingertips (2 N) and lack of sensory system (no force or tactile sensors).

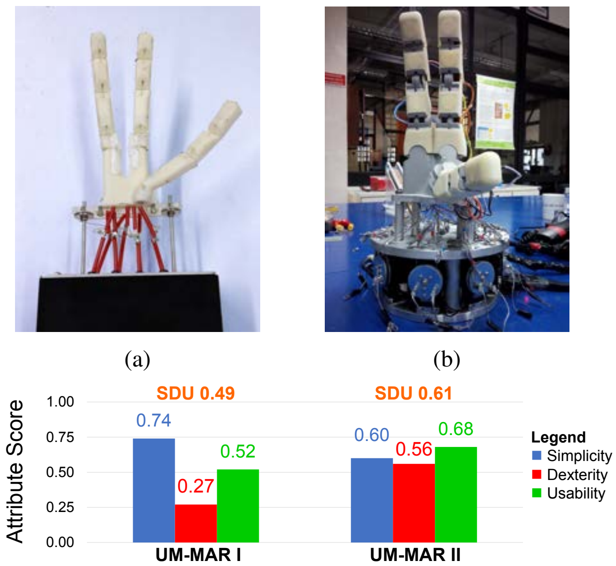
Using the derived definitions as design guidelines, the main design improvements that are implemented and design trade-offs between the attributes are described in the following section.

C. New Version of Robot Hand: UM-MAR Hand II

It was decided that the new robot hand would retain the minimal kinematic configuration proposed in [16] due its potential compact yet dexterous design. The main parameters influencing the kinematic structure (lengths, position and orientation of phalanges, and range of joint angular motion) were mathematically modelled and systematically varied. By running a number of simulations, the parameter values that satisfied the greatest number of attainable grasps, combined with an effective workspace, were identified for the final robot hand structure (strengthening $D2.2.a$).

Each phalange of the robot hand was composed of a single component, produced out of Alumide (3D printed material consisting of nylon filled with aluminium dust), hence significantly lowering the number of parts in the robot hand (Fig. 3b). A cylindrical joint mechanism was integrated within each phalange in order to simplify the design of the articulated structure of the hand (enhancing $S4.1$).

To minimize dependencies between the components, the main actuation system was located away from the robot hand. Nonetheless, the actuation system was still designed



(c)

Fig. 3: Robot hand designs: (a) *UM-MAR I* [14], (b) *UM-MAR II* [15], (c) *UM-MAR Hand I* and *II* SDU comparison.

under strict weight and size limitations to be easily coupled to an industrial robot arm (by following $Si.4$). Smart servo motors were selected due to their enhanced capabilities over traditional servo motors, such as: control over various parameters (velocity, compliance, enhancing $D1.3a$), and highly enriched feedback information (velocity, torque, enhancing $D1.3b$).

Force sensitive resistors (FSRs) were incorporated at the phalanges of the new robot hand for tactile feedback. Additionally, piezo-resistive flex sensors were incorporated at the joints to measure the flexion/extension angles. Apart from enhancing $D1.3b$, the small-scaled size ($S2.4$) of the sensors greatly complemented the design of the robot hand.

For the user interface of the robot hand, different hand-tracking vision systems were considered. The main benefit of these systems is that they do not hinder the natural movements of hand motion ($U1.3$). Hence, a Leap Motion device [18] was selected as the main means of interpreting the user's hand posture to control the robot hand.

It can be noted that the dexterity (0.56) and usability (0.68) attributes of the new system are improved over the previous robot hand at some cost of simplicity (0.60). As a result, the overall SDU score increased to 0.61 (as shown in Fig. 3c). The dexterity of the new robot hand is mainly enhanced due to its direct control over joint position and velocity, improved fingertip forces and optimized physical specifications. The usability attribute is mainly improved due to the incorporation of the Leap Motion device, allowing the user to control the robot hand using natural hand movements.

V. CONCLUSION

The main aim of this work was to identify the factors that influence the design attributes under consideration (simplicity, dexterity and usability) of CMDOF devices. A multi-parameter evaluation system based on these three attributes was developed and referred to as the SDU framework. By quantifying these factors and their compound scores, this could measurably improve the design of CMDOF devices. As a case study, the approach was used to augment the design of a minimal anthropomorphic robot hand, and demonstrated improved SDU score results.

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