

The University of Malta Minimal Anthropomorphic Robot (UM-MAR) Hand II

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Abstract—A minimal anthropomorphic robot hand is under development in the Faculty of Engineering at the University of Malta. The basic design is based on previous work in the faculty that has shown quantitatively that acceptable dexterity can potentially be achieved using a ten joint, eight degree-of-freedom hand that incorporates a thumb, two fingers, and effective touch sensing and hand control systems. The second test version of this hand, UM-MAR Hand II, has been built and is presented in this work. The approach taken in the development of this second prototype focusses on enhancing three fundamental and often conflicting attributes of compact multi-degree-of-freedom systems, identified as the simplicity, dexterity and usability of the device. In particular, extensive simulation work is carried out to optimize the fixed Denavit-Hartenberg parameters of the hand, as well as the joint ranges, in order to achieve human-like grasping dexterity with the reduced kinematic configuration. The design, development, construction and early evaluation of the UM-MAR Hand II are described in detail.

I. INTRODUCTION

The human hand is the sole prehensile human organ that permits effortless grasping and manipulation of objects. Despite this, its mechanical counterpart as a robot device has often led to highly complicated designs, that not only attain limited grasping and manipulation performance, but are also impractical to be used outside laboratory premises. The superior dexterity of the human hand is attributed to its complex lightweight biological mechanisms. Over the years, a practical mechanised replication of the human hand has proved to be rather technologically difficult using traditional engineering methods.

As a consequence, the development of a feasible robot hand entails a sensible trade-off between the incorporated mechanisms and the extent of dexterity offered by the device. In view of this, a set of design guidelines based on a detailed empirical study has been presented in [1], aimed at simplifying the kinematics of the robot hand while retaining an acceptable level of measurable dexterity. Based on the results of the study, the authors proposed that a simplified yet dexterous robot hand needs to incorporate (i) two adjacent fingers (index and middle fingers), and a thumb; (ii) the corresponding MCP and PIP joints of the fingers; (iii) the DIP joint coupled to the PIP joint, with an angular ratio of 2:3; (iv) an abduction/adduction joint between the two fingers, that must have an angular range of motion of about

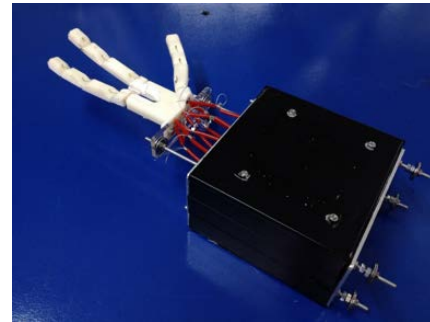


Fig. 1: UM-MAR Hand I [2].

30°; (v) a thumb consisting of at least three carefully selected DOFs; and (vi) an effective sense of touch.

This resulted in a proposed kinematic structure with 10 DOFs, 8 of which are independently actuated. The authors claim that the proposed minimal anthropomorphic artificial hand could potentially achieve a dexterity level of 84%, provided that the device is coupled with the control, actuation/transmission and vision systems equivalent to that of the human.

Following the proposed kinematic configuration, a robot hand that satisfied the requirements (i) to (v) above was developed, referred to as *UM-MAR¹ Hand 1* [2] (Fig. 1). Apart from maintaining a minimal kinematic structure, other design simplification features were applied to the overall mechanical design of the system. The actuation system, consisting of a series of compact electric linear actuators, was located in the forearm of the system in order to ease the design constraints on the articulated robot hand structure. A series of tendon cables were used to link the actuators to the articulated hand structure. The articulated parts of the robot hand were produced out of ABS polymer using fused deposition modelling (FDM) technology, entailing a lightweight design. This type of fabrication technique facilitated the development of a novel joint mechanism, which required very specific yet minimal geometric features. Elastic elements were incorporated at each joint, permitting easy joint flexion, whilst at the same time being compliant to external collisions.

The robot hand could be controlled either using a set of rotary potentiometers knobs (high accuracy however impractical for frequent use) or using a data-glove consisting of embedded piezo-resistive sensors (more comfortable to use, less accurate). The great majority of grasps outlined by

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¹University of Malta - Minimal Anthropomorphic Robot

Cutkosky [3] could be performed by the robot hand, despite its minimal kinematic configuration. However, *UM-MAR Hand I* had certain deficiencies in dexterity, most particularly being a non-optimized range of object sizes that could be grasped, low maximum fingertip forces (approximately 2 N), no tactile feedback, and no means for interpreting the joint positions and velocities.

Realizing this problem, a generic design framework (see [4], and summarized in Section II below) has been developed and is intended to improve the design effectiveness of devices that are subject to constraints similar to those of robot hands.

Hence, a new robot hand aimed at having an improved design effectiveness over the *UM-MAR Hand I* is presented in this work; the new robot hand is referred to as *UM-MAR Hand II* hereinafter. By following the presented design framework, *UM-MAR Hand II* is intended to have improved levels of dexterity over its predecessor. Moreover, alternative means other than glove-based systems for teleoperation of the robot hand are explored throughout this work, in order to improve the usability of the device. These design improvements are meant to be achieved without significantly compromising the design simplicity of the robot hand.

II. DESIGN IMPROVEMENT FRAMEWORK

The design improvement framework focusses on addressing directly the simplicity, dexterity and usability attributes of mechatronic devices that execute multiple motions while following strict weight and space constraints. Such devices are herein referred to as *compact, multi-degree-of-freedom* (CMDOF) mechatronic devices. In general, CMDOF devices do not necessarily need to have an anthropomorphic structure. Other examples of CMDOF devices include domestic cleaning devices [5], medical manipulation tools [6], and space exploration devices [7].

In brief, the *simplicity* attribute refers to the device features which result in a less complex design, enabling it to be more easily produced and to be potentially more reliable in operation. The *dexterity* attribute, which in common usage and in literature is usually associated with the abilities of a hand, will have its definition extended for the purpose of this work such that it describes the motion-related performance capabilities of any CMDOF device. Lastly, the *usability* attribute refers to the qualities of the device that enable easy operation by the user. A device that excels in all the three attributes is considered to possess a highly effective design. Maximizing the three attributes simultaneously is perhaps a difficult task due to their apparent conflicting nature. As a consequence, achieving a sensible trade-off is of paramount importance in this regard. For each attribute, the influencing factors have been identified, and thus these should be enhanced for an effective design.

For high *simplicity* a device should have a low number of components that furthermore are plain and straightforward. This can be achieved by reducing the design features present in the design (e.g. holes, extrusions) [8] and auxiliary components (e.g. bolts, mounting brackets). Moreover,

design simplification can be enhanced by designing components that are similar and share common features (including their interfacing connections), hence promoting a modular design [9]. Designing components that are totally independent (i.e. do not depend on, or are not responsible for, other components) is also likely to simplify the design [10]. Finally, developing compact components, by reducing their weight and size, is likely to alleviate the design constraints imposed on the remaining components of the system, thus simplifying the overall design.

The *dexterity* of the device can be improved by enhancing several factors. One of the influencing factors is the attainable effective motion capabilities of the device [11]. Enhancing the translation and rotational motion capabilities is likely to enhance the dexterity of the device, as larger and more versatile operating workspaces are attained. Designing a device that meets easily the expected functional and accuracy requirements also enhances its dexterity as defined in this work. Furthermore, a device that is capable of controlling as well as attaining feedback of the position, velocity, force and other related parameters of the device entails improved dexterity [12]. A last factor that greatly influences the dexterity of the device is its generalized flexibility. The flexibility of the device can be boosted by improving the mechanical compliance of the device and by improving the adaptivity of the controller to cope with external elements (e.g. impact forces) [13].

The factors that should be enhanced to improve the *usability* attribute include the enhancement of the device autonomy. This may be achieved by enhancing the degree of control abstraction exhibited at the user interface (i.e. hiding the complexity of the device from the user), and also by enhancing the ability of the device to take its own decisions [14]. Moreover, a user-interface that highly resembles the device, both in terms of structure and behaviour (e.g. forces) is likely to render the device easier to operate [15]. User-friendliness also plays an important role for the operability of the device. A highly usable device can be described as one that requires minimal effort/skill from the user for its operation, whilst at the same time having a highly ergonomic user-interface. Finally, a desirable characteristic of a usable device is interaction agility. Hence, improving the immediateness of the device action following the issuance of the operator's instruction, whilst also being capable of performing immediate adjustments to the user inputs (for example in the case of any unexpected circumstances) is likely to enhance the usability attribute of the device [16].

Further details about the design improvement framework, including quantification aspects of each attribute, are given in [4].

III. DEVELOPMENT OF UM-MAR HAND II

A. Introduction

The identified factors pertaining to the effectiveness of the design offer a useful means of supporting the design and development of generic CMDOF mechatronic devices. Throughout this section, the presented design framework is

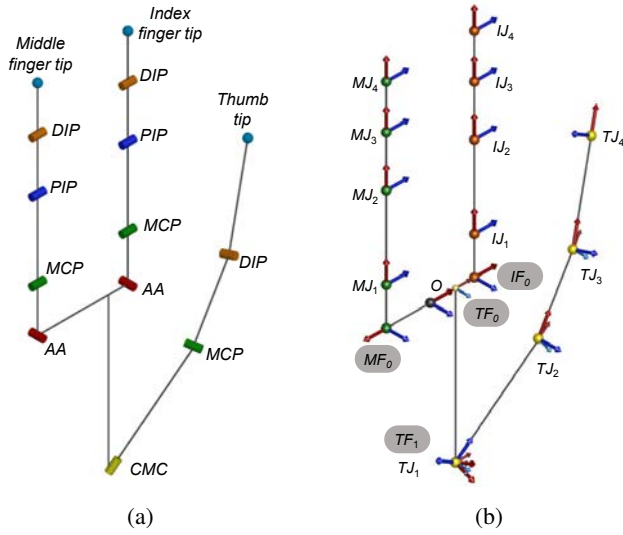


Fig. 2: Robot hand design: (a) Kinematic structure, (b) Illustration of the optimized variable DH parameters and fixed DH parameters (the latter are shaded).

applied to the development of the *UM-MAR Hand II*, such that design improvements over the *UM-MAR Hand I* are attained.

B. Kinematic Configuration

It was decided that the new robot hand would be based on the reduced kinematic configuration proposed in [1] (Fig. 2a), as this could potentially lead to a relatively simpler design whilst retaining a high level of dexterity. This section is targeted at extracting the critical kinematic parameters of the new robot hand, such that an effective grasping performance is attained by the design.

The proposed hand configuration was mathematically modelled using the Denavit-Hartenberg (DH) matrix representation. The fixed DH parameters (lengths, position and orientation of phalanges) and the ranges of the variable DH parameters (joint angular motions) were optimized with respect to the grasping capabilities and effective workspace of the robot hand. Fig. 2b illustrates all the reference frames that were investigated in order to optimize the outlined parameters.

For every candidate set of parameter values, all the attainable tip positions of the fingers and the thumb were plotted onto scatter charts showing the the attainable positions of the two finger tips and the thumb tip (Fig. 3a). These scatter charts permitted an evaluation of the workspace of the kinematic hand. Precision and power grasps (Fig. 3b and 3c, respectively) were then simulated by introducing objects of different shapes and sizes inside the scatter charts. A set of parameters that attained a higher number of coincident points between the finger tip positions and the periphery of the objects was deemed to be more successful.

The different kinematic parameter sets that were applied resulted in different grasping and workspace results. In summary, it was found to be better to have phalangeal lengths in anthropomorphic ratios (especially for precision grasps);

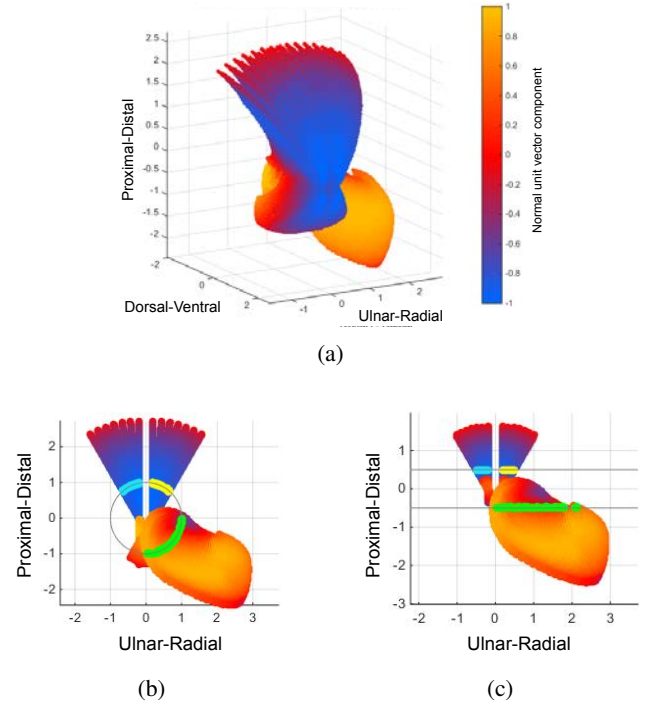


Fig. 3: Scatter charts: (a) 3D scatter illustrating the achievable workspace for a hand with a specific set of kinematic parameters, (b) Precision grasp of an arbitrary object with circular geometry, (c) Power grasp of an arbitrary object with prismatic geometry. Note: The objects with specific geometries are represented by the outlines in charts (b) and (c).

increase PIP joint ranges; small twist angles for the DIP and MCP joints; the thumb closer to the palm centre; and a thumb rotation range of about 160° .

Following the simulations and these observations, the most potentially successful kinematic parameter set was selected for *UM-MAR Hand II*. In the remainder of this section, the important design aspects related to the mechanical design of the robot hand are described.

C. Joint design

As the joints of the robot hand constitute a very significant feature of the device, significant effort was applied to develop a simple yet effective joint mechanism. The developed mechanism is mainly an adaptation of the cylindrical joint (Fig. 4), mimicking the geometrical features found in the human hand joints. The joint permits its upper adjacent phalange to revolve about the central axis of the cylinder when pulled, mimicking the flexion motion of the human joint. As opposed to a traditional hinge mechanism, the proposed joint has simple design features, without significant addition of auxiliary components. The cylindrical joint was implemented to all joints of the robot hand to minimize design variations.

D. Actuation and Sensory System

For the actuation system, smart servo motors were selected for the actuation of the robot hand. In the literature,

these type of motors have been successfully implemented in small-scaled humanoid robots (e.g. [17]). These servo motors offer enhanced capabilities over traditional servo motors, such as flexible control over various parameters (velocity, compliance), highly enriched feedback information (velocity, torque, temperature, current load) and easy network communication (daisy chain link). Eight Dynamixel RX-24F smart servo motors [18] were incorporated in the robot hand design. Similar to the *UM-MAR Hand I*, the actuators were remotely located from the hand site. Transmission was provided via a set of tendon cables produced out of Dyneema fibres (1 mm diameter).

As indicated in Section I, the dexterity of the device would be enhanced by incorporating an effective tactile sensory system. The minimum requirements for an effective touch sensor have been investigated in a complementary study [19], that suggested that a force sensitivity of around 20 mN and a two-point discrimination capability of 5.6 mm would be required. However, these requirements demand for a highly specialized sensor that has not yet been developed or otherwise acquired. Provisionally in this work, it was decided to opt for commercially available sensors, and thus force sensitive resistors (FSRs), were used to act as a tactile feedback system for the robot hand. Future work is targeted at developing an improved tactile sensor with improved characteristics, including two-point discrimination capability. In addition, bend sensors were included to the sensory system of the robot hand, for controlling the angular position of the robot joints using closed loop control. Both types of sensors consist of simple geometry and compact sizes making them highly suitable for the robot hand.

E. Detailed Design

The individual phalanges of the robot hand are perhaps the mostly constrained components in the design, due to their requirement of satisfying a number of geometrical functions. Specifically, these links must be designed such that they enable relative motion between each other, are able to host the sensory elements, support internal loads, and provide access to tendon cables. All of these geometrical functions must be incorporated within a highly restricted workspace, such that overall dimensions reflect those of the human hand.

A pocket has been designed on the surface of each phalange such that it allows the FSR sensors to be easily embedded (see Fig. 4). A cavity with a profile shape of the bend sensors was also designed at one side of the phalanges, which intersects across two adjacent phalanges. When the finger is bent, this causes the sensor that is passing through the two phalanges to bend according to the angle produced by the two phalanges. Internal passageways were also designed inside each phalange, allowing the tendon cables to easily pass through the robotic fingers.

The individual links of the robot hand were fabricated out of Alumide (nylon material filled with aluminium dust), using a Selective Laser Sintering (SLS) process which enabled intricate geometries to be easily produced. Alumide possesses superior mechanical properties over

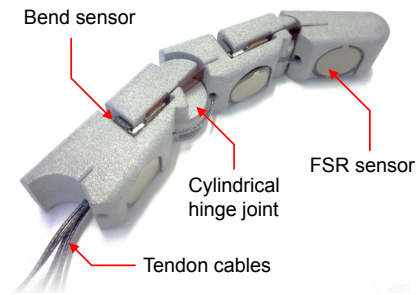


Fig. 4: Robotic finger produced out of Alumide, incorporating the sensory elements.

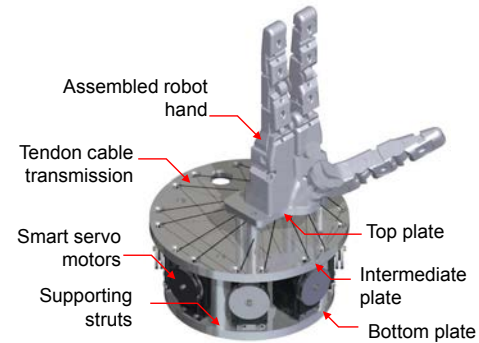


Fig. 5: CAD model illustrating the robotic hand mounted on the aluminium supporting structure.

traditional materials used in 3D printing (such as ABS), most particularly it is rigid and is able to resist some degree of bending. A post-process polishing procedure was conducted to smoothen the surfaces of the parts to reduce frictional effects at the joints.

The actuation system is incorporated within an aluminium frame structure mainly consisting of plates that rest on top of each other using a set of struts, as shown in Fig. 5. To minimize the frictional effects, smooth rounded edges were machined through the passing holes, which mimicked the function of a free-rolling pulley.

F. Teleoperation of Robot Hand

Alternative means to a glove-based system for teleoperating the robot hand were investigated. By following the identified factors related to the simplicity and usability attributes, it was noted that a hand-tracking vision system is likely to be more suitable to teleoperate the robot hand. A hand-tracking vision system does not require any attachments to the user's hand, as opposed to glove-based systems, potentially resulting in a system with high levels of control abstraction and user-friendliness. Hence, the Leap Motion device (possessing an accuracy of 1.2 mm for dynamic motions) [20], was selected as the main user-interface for the robot hand.

G. Control of Robot Hand

The Leap Motion and the Dynamixel servo motors were interfaced to the computer using Visual Studio C++. The

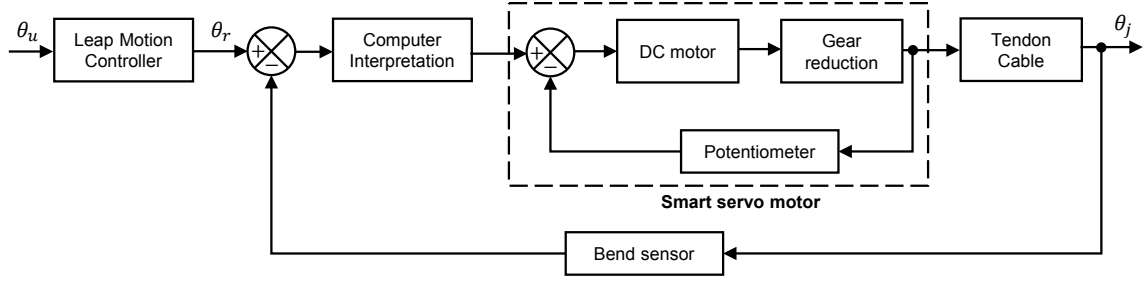


Fig. 6: Control of robot hand system (Note: θ_u = user's joint angle, θ_r = reference signal, and θ_j = robot joint angle).

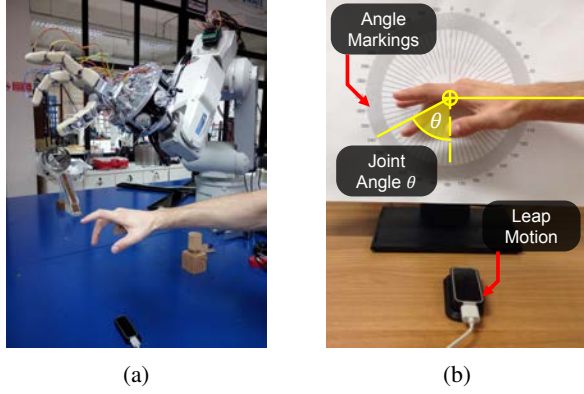


Fig. 7: Leap Motion device: (a) Control of robot hand via gesture recognition, (b) Experimental setup for measuring finger joint angles using Leap Motion device.

FSRs and bend sensors were interfaced to an Arduino Mega 2560, which served as the analogue-to-digital conversion unit. Each analogue input of the microcontroller provided 10 bits of resolution over 5 V, resulting in 1024 different values. A schematic representation of the control system is shown in Fig. 6. The finalized *UM-MAR Hand II* being operated through the Leap Motion device is shown in Fig. 7a.

IV. EVALUATION OF UM-MAR HAND II

The performance of the Leap Motion device was evaluated in order to maximise its performance during teleoperation. Hence, an experiment was designed to measure the user's joint angle using the Leap Motion device, as shown in Fig. 7b. From the obtained results, it was noted that in general a linear relationship was followed between the user's joint angles and Leap Motion measurements, below a specific threshold value. A deadband was exhibited by the device above the threshold value. This threshold is approximately at 60° and 80° for the MCP and PIP joints, respectively. To rectify this issue, the attainable range of the user's joint angles was scaled accordingly in order to match the readable range of the Leap Motion controller.

An evaluation of the feedback loop of the joint positional control (described in Section III-G) was conducted. In general, it was noted that the system already performed fairly well in open loop, as the maximum error in the angular position was $\pm 10.3^\circ$. With the use of the feedback system,

the error was reduced to $\pm 5.3^\circ$. It is noted that this error is acceptable for this device, since the system is intended to be used with vision feedback, primarily in teleoperation applications. Presently, the prototype uses a proportional controller. Upgrading to an integral controller would improve further the accuracy of the position control system.

An experiment was also conducted to measure the maximum forces produced at the fingertip, using a spring balance. Fingertip forces of 7 N and 10 N, respectively, were produced when the MCP and PIP joints were actuated individually. The fingertip forces produced by the robot hand could possibly be improved by reducing the frictional effects exhibited inside the internal passageways of the robot hand.

An extensive evaluation of the grasping capabilities of the robot hand was conducted. In general, the hand was able to perform all the required grasps, and in most cases a highly natural grasp was retained as indicated in Fig. 8. It was noted that, for smaller objects, a different posture from the human hand was required in some instances to accommodate the size of the object.

The complete robot hand system weighs 3.8 kg. Most of its weight is attributed to the aluminium supporting structure, as the robot hand itself and the actuators weigh only 0.4 kg and 0.5 kg, respectively. The distance between the base of the robot hand and the finger tips is 214 mm. The eight servo motors, connected in a daisy-chain fashion, require 12 V to operate, and are capable of producing a maximum (stall) torque of 2.5 Nm each. The FSR sensors mounted on the surface of the robot hand are capable of measuring forces of up to just under 10 N.

The *UM-MAR Hand II* possesses improved dexterity and usability attributes, compared to its predecessor design. Enhancements in the dexterity are mainly due to the refined control system, improvements in the fingertip forces, as well as improved grasping capabilities. Additionally, the integration of a hand-tracking vision system greatly improved the usability of the new robot hand, compared to the previous robot hand which was controlled using a data-glove. These design improvements were attained at a slight penalty in simplicity. However, an overall design improvement of the new robot hand was achieved, as careful design trade-offs were taken using the design improvement framework.

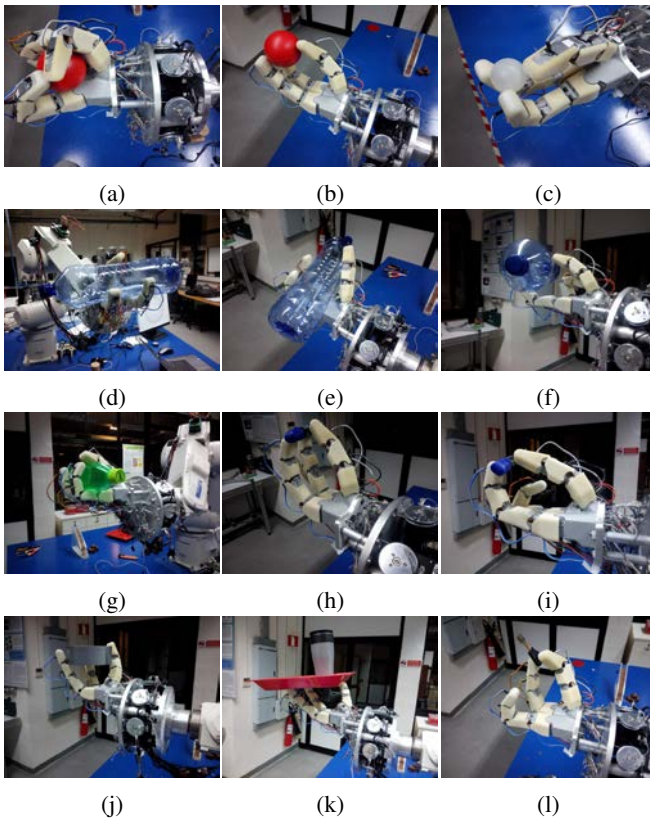


Fig. 8: Robot hand grasps: (a) Circular power grasp of medium-sized object, (b) Circular precision grasp of medium-sized object, (c) Circular precision grasp of small object, (d) Wrap power grasp of large object, (e) Prismatic power grasp of large object, (f) Thumb & 1 finger precision grasp of large object, (g) Wrap power grasp of medium-sized object, (h) Thumb & 2 fingers precision grasp of small object, (i) Thumb & 1 finger precision grasp of small object, (j) Disc precision grasp of large object, (k) Non-prehensile grasp, (l) Prehensile grasp.

V. CONCLUSION

The main aim of this work was to develop the second prototype of the University of Malta minimal anthropomorphic robot hand, based on a new design improvement framework for CMDOF devices. The improvements were effected through simultaneous consideration of the simplicity, dexterity and usability of the new design. In particular, design improvements in the dexterity and usability of the device were attained, at a slight penalty in simplicity, when compared to the first prototype. The dexterity of the system was enhanced by a thorough optimization of the geometric hand parameters for grasping as well as by the incorporation of compact smart servo motors and sensory elements. From the evaluation exercise, it has been observed that the robot hand has demonstrated an improved overall design over its predecessor. The next steps involve implementation of tactile feedback to the human operator, followed by an extension of the dexterity evaluation of the *UM-MAR Hand II* from the static (grasping) mode to the dynamic (manipulation) mode.

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