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Design, Development and Control of the Anthropomorphic Robotic Hand TALOS

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***Abstract* —The Control Systems & Robotics Laboratory of the Technological Educational Institute of Crete has developed an anthropomorphic robot hand, intended to serve as a general-purpose research tool for the study of robotic dexterity, grasping and object manipulation. The robot hand, which is named TALOS, has a thumb and four fingers, with a total of 16 degrees of freedom (d.o.f.). The joints are driven by RC-servo motors that are housed in the phalanges and the palm of the hand. This simplifies the mechanical configuration of the joints and has the advantage that a common RC-servo controller can independently control the servo actuators of the joints. The manufacturing process, the mechanical configuration of the joints and assembly of the robotic hand are also presented in detail, along with the control architecture which is divided into two levels and is based on the kinematic model of the robotic hand. Finally, experimental results are given to evaluate the practicability and effectiveness of the robotic hand in grasping objects and mimicking human gestures.**

Keywords—Robotic hand, multi-fingered, anthropomorphic robots, rapid prototyping, RC-servo actuators, control architecture.

I. INTRODUCTION

In Greek mythology, TALOS was a mythical bronze giant, the first robot in history, which protected Minoan Crete from would-be invaders as he could travel round the whole of Crete island three times a day [1]. TALOS was not born but made on Zeus's orders by Hephaestus, the god of fire and iron. The Minoans were so advanced that they imagined a bronze superhero to protect them. TALOS can therefore be seen as a symbol of technological development in the field of metal-working in prehistoric and Minoan times.

The Control Systems & Robotics Laboratory of the Technological Educational Institute of Crete, as honor to our ancestors, has developed an anthropomorphic robotic hand named TALOS. The robotic hand is intended to function as a general-purpose research tool for the study of machine dexterity and the development of algorithms that concern grasping and object manipulation. It can be also utilized as a prototype for developing prosthetic hands or as a slave element in teleoperation systems.

The human hand may well represent the perfect gripper, since a wide variety of complicated object manipulation tasks can be accomplished with dexterity and versatility. With this in mind, an anthropomorphic configuration is desirable for the design of a robotic hand. In addition, from an experimental standpoint, it also allows researchers to more directly compare operations of the human hand with those of a robotic hand. This helps to design new intuitive and simple algorithms for grasping and object manipulation.

A variety of multi-fingered robot hands that more or less mimic human hands have been designed and manufactured in the last thirty years (detailed surveys can be found in [2-4]). Most of these robotic hands have complicated mechanical design, with expensive actuators and very complex control architectures. Recent advancements in rapid prototyping technology (mainly 3d printing) enable us to fabricate easy and fast custom parts in shapes never before possible. As a result, several low cost 3d printed robotic hands have been developed [5-11]. All of these prototypes focus on an underactuated design that makes use of tendon drive mechanisms, in order to simplify the fabrication and assembly of the robotic hand. However, the dexterity is considerably reduced, while issues arise related to friction and the non-rigid characteristics of the tendon wires. The utilized actuators vary from servo motors [6-9] to shape memory alloy actuators [10] and pneumatic artificial muscles [11].

In the following sections we present the robotic hand TALOS, which meets the requirements of anthropomorphism with high functionality and human-like movements. The primary design criteria for TALOS were kinematic dexterity, simplicity of the control interface, low cost, and ease of fabrication. A modular design strategy has been adopted to satisfy those constraints and considerations. The resulting hand has five digits with a total of 16 d.o.f. Its overall weight is 620gr, including the digits, the palm, and the actuators with their low level control units. The actuators are encased in the phalanges of the fingers and the palm, so that all degrees of freedom can be activated independently. The estimated overall cost of the robotic hand is 260 euros.

II. DESCRIPTION OF THE TALOS ROBOT HAND

The hand prototype, shown in Fig. 1, comprises four fingers (index, middle, ring and pinky finger) with 3-d.o.f., and a thumb with 4-d.o.f. Each joint is actuated by a conventional RC-servo. The low-level control of the actuators is handled by a microcontroller placed at the backside of the palm.

A CAD drawing of the developed prototype is provided in Fig. 2. The phalanges and the joints of the robotic hand are named by adapting the corresponding terminology of the human hand anatomy. In particular, the three phalanges of each finger are named as the Proximal, the Middle and the Distal phalanx. The joint that connects the fingers with the palm is called MetaCarpoPhalangeal (MCP) joint. The joint in the middle of the finger is called Proximal InterPhalangeal (PIP) joint, and the one that is closest to the fingertip is called Distal InterPhalangeal (DIP) joint, as illustrated in Fig. 2. Each of these twelve joints of the four fingers allows a flexion/extension motion of the associated phalanx, however the fingers are not capable for an abduction/ adduction motion. To simplify manufacturing, all fingers have identical dimensions and they are placed on the palm with a slight difference in position along the palm. This allows the mechanism to be more anthropomorphic, and, in case of a malfunction of any finger, the remaining ones can replace it.

On the other hand, the thumb has similar dimensions with the fingers but it has been designed with four independent d.o.f. in order to allow grasping tasks by opposition. The joint that is closest to the palm has a considerable mobility with two independent d.o.f. and is called CarpoMetaCarpial (CMC) joint. Due to this joint the thumb is able to carry out rotary and abduction/adduction motion. The other two joints are called the MCP and DIP joints of the thumb allowing flexion/extension motion (see Fig. 2). The angular range for each joint relative to the corresponding sagittal or frontal plane of the hand is illustrated in Fig. 3. All three joints of each of the four fingers have the same range, while the 2 d.o.f. CMC joint is more versatile.

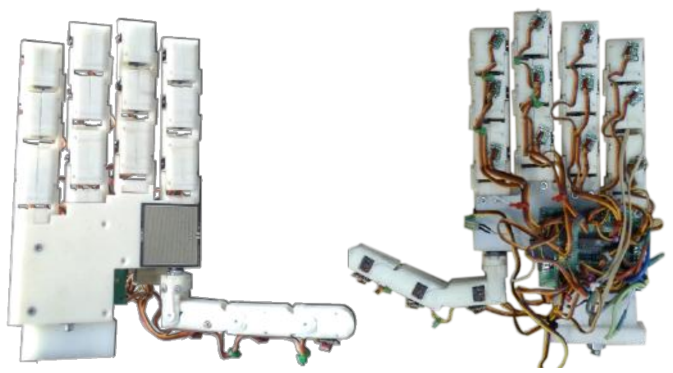


Fig.1 Front and backside of the TALOS robotic hand.

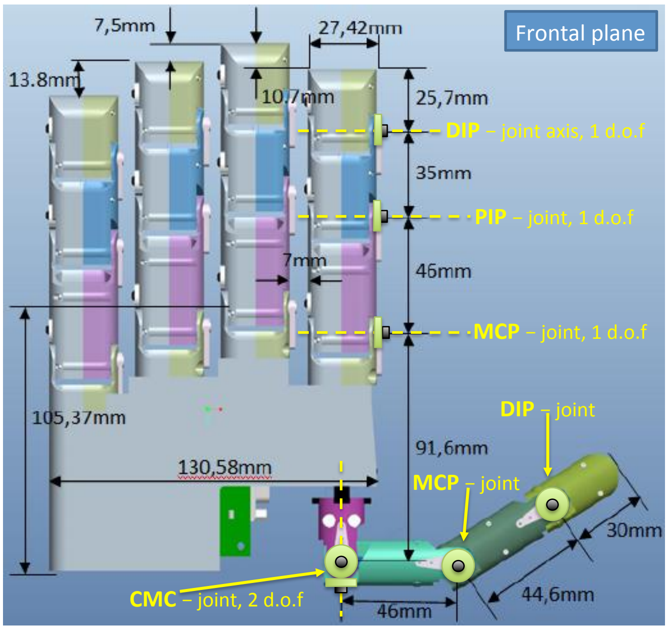


Fig.2 CAD model of the robot hand, showing its main dimensions and the naming convention for the joints.

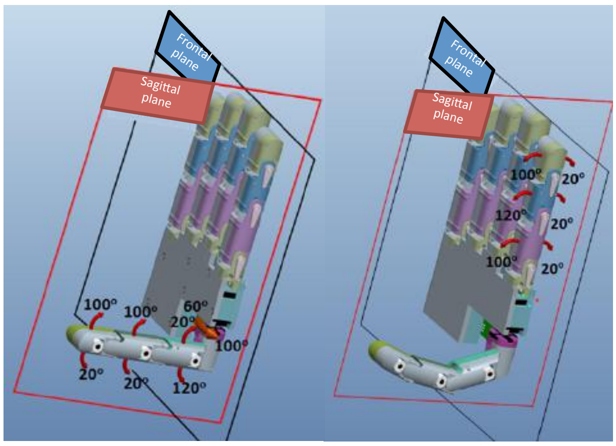


Fig.3 Range of motion for the joints of the thumb and the fingers.

More specifically, flexion motion parallel to the sagittal plane, is in the range of -20° to 100° for the MCP and DIP joints, and from -20° to 120° for the PIP joints. An abduction / adduction on the frontal plane is not possible for the fingers except the thumb, which is capable of this motion due to the first d.o.f. of the CMC joint, i.e. for -20° or 120° relative to the initial posture of the thumb shown in Fig. 2. The second d.o.f. of the CMC joint, whose revolute range is 160°, opposes the thumb to the rest of the fingers..

The robotic hand has 16 independent d.o.f driven by actuators that are housed directly inside the phalanges (Fig. 4c), with the exception of the thumb's CMC joint, where the first actuator resides inside the palm (Fig. 4d) and the second one inside the following phalange. This simplifies the mechanical configuration of the joints and reduces the complexity of the transmission chain, while offering the advantage that the joints can be mobilized independently.

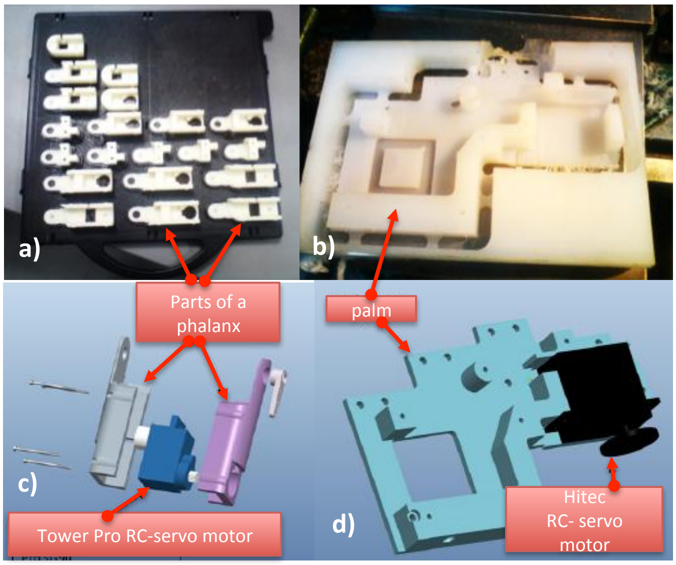


Fig.4 The CAD models and the actual manufactured parts.

In order to move the DIP, PIP, and MCP joints, a total of 14 TowerPro SG90 RC-servo motors are used, encased inside the phalanges (Fig. 4c). These are compact-size and lightweight micro RC-servos with high output power and a maximum rotation range of approximately 180°. An additional servo of this type is used for the second d.o.f. of the CMC joint, which can effect the orientation of the thumb on the frontal plane (see Fig. 2). The first d.o.f. of the CMC joint is actuated by a Hitec HS-225BB RC-servo (Fig. 4d), which has improved torque characteristics compared to the TowerPro servo. This d.o.f. enables changing the orientation of the thumb with respect to the frontal plane, and opposes the thumb to the rest of the fingers.

III. Manufacturing Process and Assembly

The robot hand weights 620gr and consists of 196 parts in total. More specifically, 42 parts comprise the phalanges and the palm with 122 screws and 15 spherical metal balls. One SSC-32 RC-servo controller at the back of the palm is utilized to control the 16 RC-servos of the hand.

All phalanges of the robot hand and the cover of the palm have been fabricated by using the fused deposition modeling (FDM) process with a Dimension Elite 3d-printer (Fig. 4a). This process allows fabricating complex 3d shapes from CAD models (Fig. 4c) easily, quickly and with low cost. The main limitation of the FDM process lies in the less-than-ideal mechanical properties of the material used, which is acrylonitrile/butadiene/styrene (ABS or ABS+). However, this is acceptable for the prototype phalanges of the hand. In contrast, the palm shown in Fig. 4b has been manufactured in a computer numerical control (CNC) milling machining center by using Teflon as raw material, which has good fabricating and machining properties, with excellent impact strength.

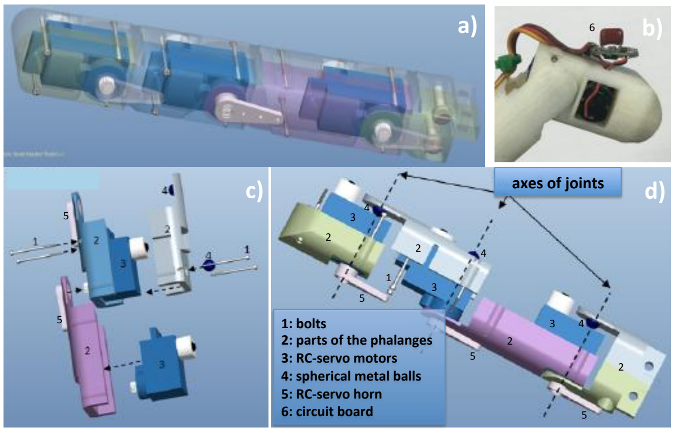


Fig.5 The basic parts of the finger module.

The assembly procedure starts from the distal phalanx, continues to the middle phalanx, and finally to the proximal phalanx along with the base of the finger. The CAD model in Fig. 5a shows an assembled finger module with the encased RC-servos. From each RC-servo motor we remove the half plastic case and keep only the mechanical and electronic parts along with the dc motor (Fig. 5b). A spherical metal ball of 5mm diameter is placed in the axis of each joint, in order to reduce friction between the two interconnecting phalanges (Figs. 5c, d).

For the assembly, a servomotor is inserted into one part of the distal phalanx as an interior shell surface and the other part is fastened through four screws (steps 1-2, Fig. 6). The electronic circuit board of the RC-servo is passed out of the body of the phalanx through a small gap (Fig. 5b). Next, the middle phalanx is interconnected with the distal one by using the servo horn and the spherical metal ball (steps 3-4, Fig. 6). The servo horn that is attached on the servo's output shaft is secured on the middle phalange using cyanoacrylate adhesive glue. Consequently, the next part of the phalanx is fastened with four screws (step 5, Fig. 6) and the procedure is repeated for each finger module and the thumb. Finally, the four fingers, the thumb and the palm, along with the SSC-32 servo controller, are assembled together as shown in Fig.7.

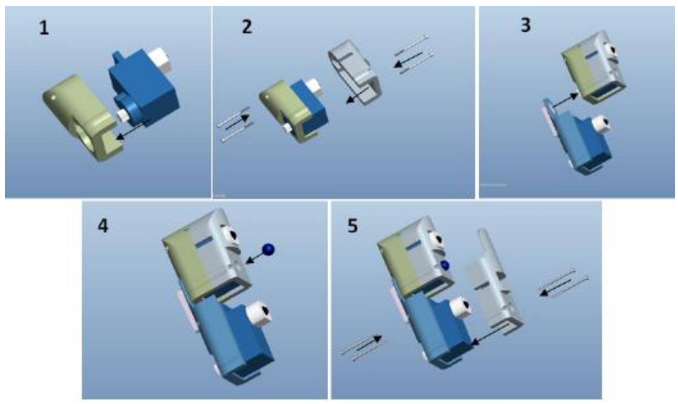


Fig.6 The steps involved in the assembly of the joint interconnecting two phalanges of a finger module.

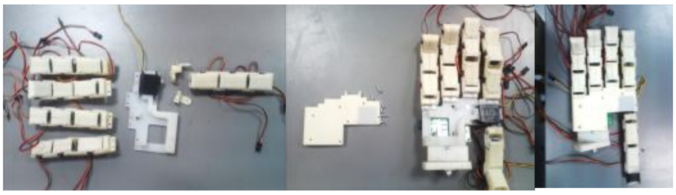


Fig.7 The final assembly of the robotic hand.

IV. Control System Architecture

The control system of the TALOS hand can be conceptually divided into two levels. At high-level, a PC is responsible for coordinating the motion of the five digits. The PC receives from the user the desired joint angles or the desired tip positions for the digits, and then it provides corresponding commands to the servo controller. At the low-level, the SSC-32 servo controller sends appropriate control signals to the RC-servos. The servos' position can also be queried to provide feedback to the host computer. The control architecture of the robot hand is schematically depicted in Fig. 8.

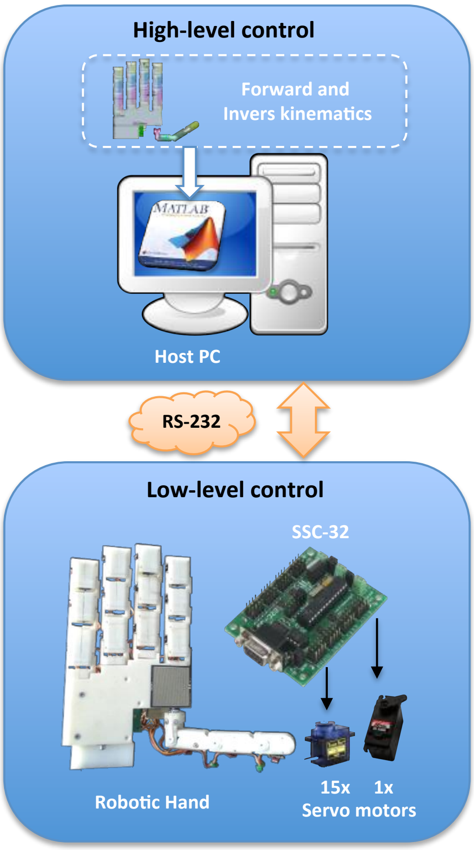


Fig.8 The control architecture of the TALOS robot hand.

At high-level, the control architecture is based on the kinematic model of the robot hand that concerns two basic functions for each digit "*j*": a) the forward kinematics function *Fwd_kinematics('j', q_0, q_1, q_2, q_3)* where q_1, q_2 and q_3 are the corresponding joint variables for the digits, while q_0 is used solely for the extra d.o.f. of the thumb, and b) the inverse kinematics function *Inv_kinematics('j', x, y, z, phi)* where *x*, *y*, *z* are the desired coordinates for the digit's tip with respect to the base coordinate system of the palm. Also the input *phi* is the desired orientation of the finger relative to the frontal plane of the palm, or the desired orientation of the thumb relative to the sagittal plane of the palm (see Fig. 2).

The SSC-32 is responsible for the low-level control of the robot hand. It is a serial servo controller with 32 channels for controlling the angular position of RC-servo motors. The PWM control signal for each servo motor varies from 500μs to 2500μs for a range of about 180°. It has 1μs resolution for accurate positioning along with smooth trajectories for the drive shaft of the servomotors. The motion control has immediate response and it is possible to set the settling time for each controlled motion. A unique "Group Move" mode allows any combination of servos to begin and terminate their motion at the same time, even if for different desired angles. This is a very powerful feature for creating anthropomorphic motions.

Every RC-servo motor is calibrated in order to map the desired joint angle to the corresponding μs command PWM_{qi} for the SSC-32 RC-servo controller. The following formula is used:

$$PWM_{qi} = \text{round}\left(k_0 - \frac{k_0 - k_1}{90^\circ} q_i\right),$$

which is a linear combination of the desire angle q_i where k_0, k_1, are calibration parameters in μs.

V. Experimental Results

When people use objects in everyday tasks, the choice of grasp is dictated less by the size and shape of objects and more by the intended task, as in holding a hammer or picking up a pencil. According to this argument, grasps can be divided into *power grasps* and *precision grasps* [12]. Power grasps are characterized by large areas of contact between the grasped object, the palm, and the surfaces of the fingers, with little or no ability to impart motions with the fingers. By contrast, in precision grasps the object is held with the tips of the fingers and thumb, while dexterity predominates over stability and security. In order to assess the kinematic capabilities of the robot hand TALOS we conducted a number of experiments that concern the former two types of grasping.

Experimental results from these tests are provided in Fig. 9. The robot hand is able to implement envelope grasps for a number of everyday objects like a plastic bottle, a glass of liquid, and a paper box with cookies as well as grasps that involve tools such as a glue gun or a paintbrush. The precision grasps for a credit card and a small ball are also shown in the same figure.

It is important to note that we don't use any force or torque sensor in order to grasp the objects. For each grasp, the configurations of the five digits are *apriori* known and the host PC simply sends the desired joint angles to the RC-servo controller. Hence, for the precision grasps any disturbance of the object may lead to instability and loss of contact with the object. By contrast, the envelope grasps are generally more stable, especially when the grasped object can be slightly deformed from its nominal shape.

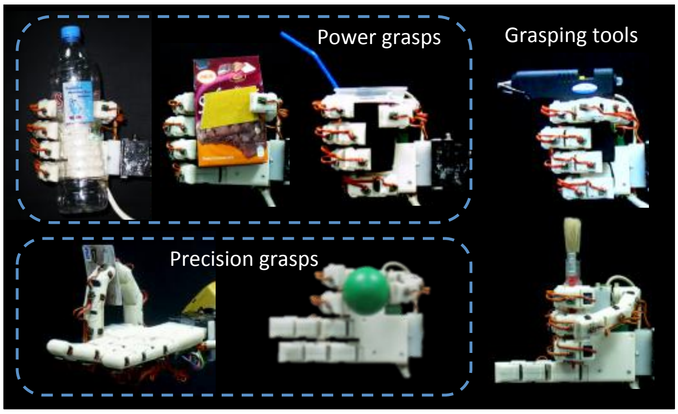


Fig.9 Different types of grasp, implemented with the TALOS robot hand.

In addition to grasping an object, the TALOS prototype can perform several hand gestures, like the "thumbs-up" sign, the clenched hand, the pointing gesture, or the Right-Hand Rule gesture (Fig. 10a-d). Moreover, since our robotic hand is capable of thumb opposition, it has the ability to turn and rotate the thumb so that it can touch each fingertip (Fig. 11a-d). This enhances in-hand versatility, since the workspace of the robotic hand is increased.

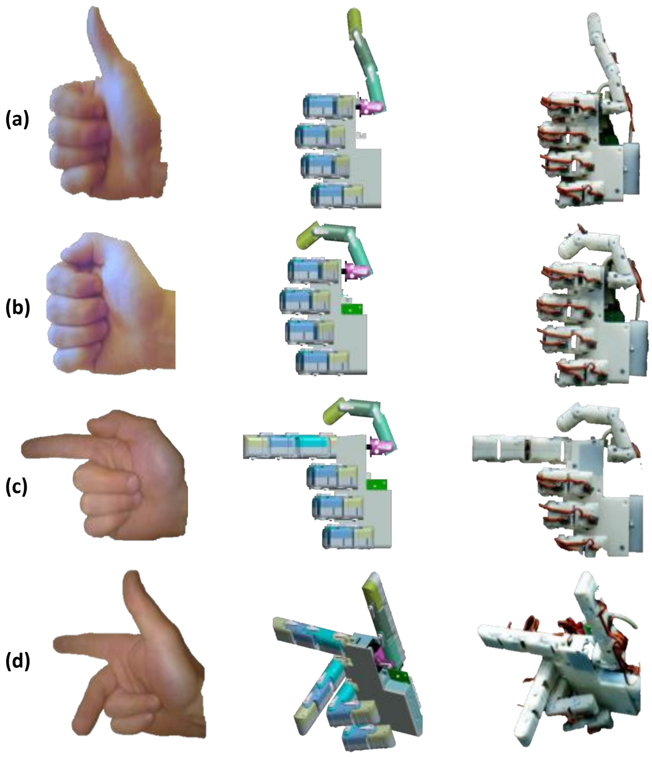


Fig.10 Robotic versus human hand gestures

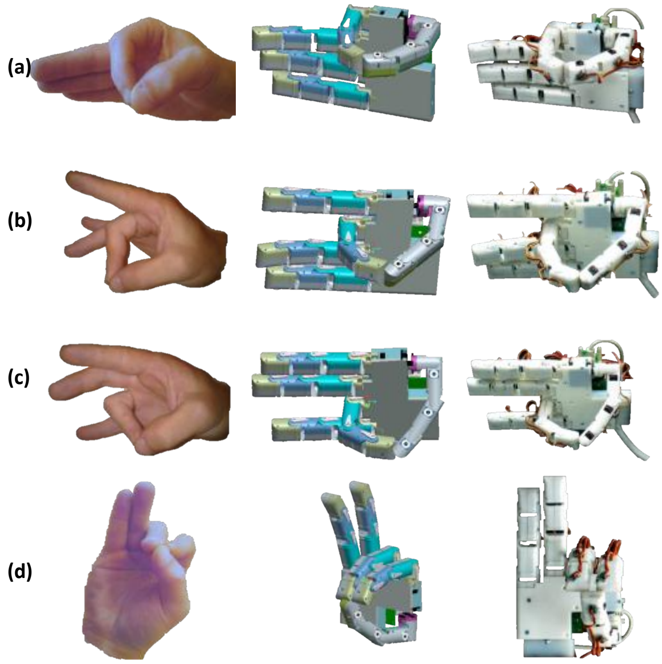


Fig.11 Robotic versus human thumb opposition

Indeed, a common in-hand manipulation task is to grasp a small object with two or three digits, in order to deliver it to another location within the hand. In this case, a collision-free trajectory has to be planned, which can be accomplished by planning a desired trajectory for the object and solving the inverse kinematics problem for the tips of the digits that are involved in the task. Based on this methodology, and utilizing the inverse kinematics function *Inv_kinematics('j', x, y, z, phi),* we conducted successful experiments concerning the in-hand manipulation of a plastic spherical object. The designated task was to move the green spherical ball into a predefined square trajectory through the path points 1-2-3-4-1, as illustrated in Fig. 12.

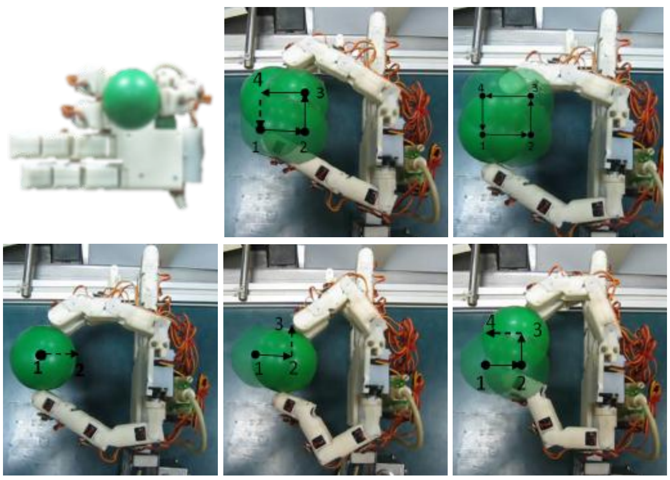
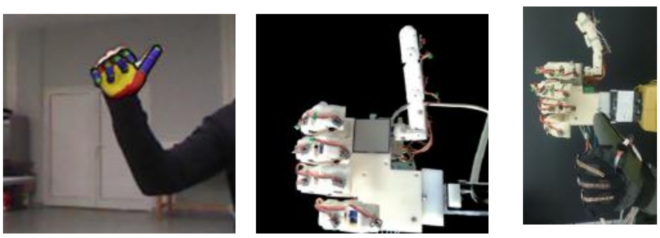


Fig.12 In-hand manipulation of a plastic ball based on path planning and inverse kinematics.

Due to its anthropomorphic configuration, the TALOS robot hand has significant potential as a slave element in teleoperation applications. In fact, two different systems have already been developed as master devices for teleoperation setups where TALOS is the slave element. This highlights potential uses of the prototype hand as a research device aimed at studying issues that influence the performance of remote manipulation systems.

In the first setup TALOS is mounted on a 6-d.o.f. robot manipulator (Mitsubishi RV-2A) that is responsible for the motion of the robotic hand, used as a dexterous end-effector, in 3d space. The integrated 22-d.o.f. slave (TALOS with RV-2A) is teleoperated by the hand movements of a human operator, which are tracked with a Kinect RGB-D sensor (Fig. 13a). This setup does not require the user to wear any motion capture glove or other exoskeleton device. The main task for the robotic system is to reproduce in real time the user's hand configurations for grasping objects or doing human gestures. The control algorithm is based on the "3d Hand Tracking" software [13], developed at the Computational Vision & Robotics Laboratory of FORTH-ICS. Experimental results that demonstrate the effectiveness of the proposed telemanipulation system can be found in [13].

The second system consists of a custom-made "data glove" unit that is equipped with 11 flex sensors in order to capture the motion of the thumb and the fingers of the user's hand (Fig. 13b). A Bluetooth-based communication scheme allows for wireless operation of this setup. A detailed description, along with experimental results that evaluate the practicability and effectiveness of the application system, can be found in [14].



(a) (b)

Fig. 13 Experimental results by utilizing teleoperation systems based on visual data or a custom data glove.

VI. CONCLUSIONS

This paper presented the development of TALOS, an anthropomorphic robot hand, of modular design, which can be attached as a dexterous gripper to life-size humanoid robots or industrial robot manipulators. We also presented successful experiments for mimicking human gestures and grasping tasks that demonstrate the kinematic versatility of the robotic hand. In order to improve the grasping capabilities of the system, future work will consider the development of an appropriate sensing system to measure the contact forces and the corresponding torques at the joints during grasping tasks. Finally, an improved version of the robot hand is currently under development, utilizing CNC-milled aluminum, rather than 3d-printed, parts, in order to improve the stiffness of the hand and the ability to exert higher contact forces.

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