DEXTEROUS ROBOTIC HAND MA-I *
Software and Hardware Architecture

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Abstract

This paper describes the main features of the dexterous robotic hand "MA-I" designed and built at the Institute of Industrial and Control Engineering (IOC) at the Polytechnic University of Catalonia (UPC). The hand is a 16-degree of freedom (16 DOF), multi-fingered general-purpose manipulator, which forms part of an integrated system for the experimentation and testing of object grasping and manipulation strategies. Hardware and software characteristics are described, including mechanical, electrical, electronics and control aspects.

Key Words: Robotics, Mechanical Hand, Grippers, Grasping, Manipulation.

1. Introduction

Robot end effectors have evolved to a highly-specialized degree, and although these tools are highly sophisticated and capable of doing complex tasks the tradeoff is that their versatility is limited compared, for instance, with the human hand. The search for flexible end effectors has become an important research field and, besides, the development of grasping strategies to determine optimum grasp according to some criteria has also become an interesting related research area [1] [2] [9] [10].

Considering the enormous range of tasks that the human hand can execute it becomes a natural model for the development of dexterous end effectors. A human hand has more than 25 degrees of freedom (DOF), which allows it to have multiple grasping and manipulation configurations with different combinations of its palm and fingers. Basically, each finger has two articulations with one rotational DOF (the distal and medium articulations) and a third articulation with two rotational DOF (the proximal articulation). The five fingers sum 20 DOF while the others DOF are in the palm. In addition to the relatively high number of DOF, the human hand has a complex sensory system that allows the perception of several characteristics of the grasped object and also gives information about the object responses to the applied forces. The information that may be acquired through the hand includes weight, dimension, inertia, composition, relative position and motion, temperature, texture and existence of external forces, among others.

Mechanical tools that try to reach dexterity comparable to the human hand, from the point of view of versatility of movements, are refered to with different names, such as general purpose manipulator, dexterous robotic end effector or mechanical hand. The principal purpose of these kinds of tools, couplep to a robot arm, is to execute different grasping and manipulation tasks of objects with multiple forms and sizes. These tools are designed keeping in mind the execution of tasks in hazardous environments or in places inaccessible to human. They are also precursos towards a general porpose tool for automation.

Several research centres have been working for many years in the design and construction of mechanical hands, trying to find an optimum relationship between dexterity, mechanical complexity, usefulness and cost (see for instance [1] [4] [5] [6] [7] [8] [12] [13]). Nevertheless, there is still a long way to go (see [1] for a survey).

In this context, this paper describes the main features of the dexterous robotic hand "MA-I", shown in figure 1, which was designed and built at the Institute

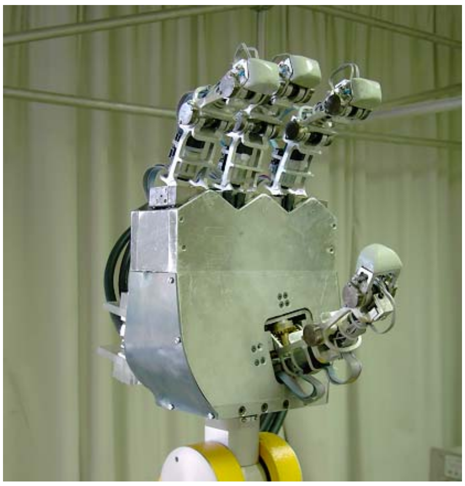

Figure 1. Robotic Hand MA-I.

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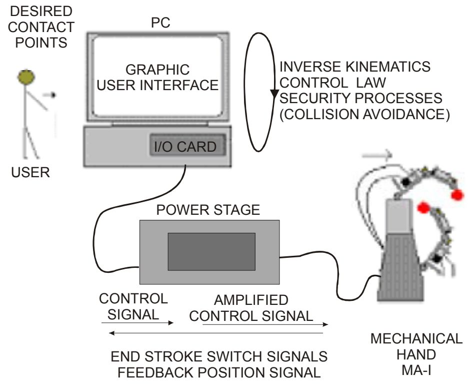


Figure 2. Systems general scheme.

of Industrial and Control Engineering (IOC) at the Polytechnic University of Catalonia (UPC). The hand is a 4-fingered general-purpose manipulator with 16-degrees of freedom (DOF), which forms part of an integrated system for the experimentation and testing of object grasping and manipulation strategies. The main hardware and software characteristics are described in the paper, including mechanical, electrical, electronics and control aspects.

2. Design framework.

Three main aspects were considered in the design framework of the hand: modularity, mechanically self-contained and human-like kinematics.

Modularity: As the system intends to be an experimental platform, clear boundaries between subsystems and easy of connectivity between them were priorities to be held in the design in order to facilitate the replacement of any part. This criterion was applied to both, software and hardware (for instance: use of different sensors or different control laws).

Mechanically self-contained: This means that all the mechanical parts should be contained in the hand itself, allowing to be coupled with any robot arm in an easy way with very little effort (for instance: avoiding tendons or motors locate on the forearm).

Human-like kinematics: As stated before, the human hand has been considered as a good model of a general purpose grasping tool, thus anthropomorphic features and ratios were considered. A scale factor was used to keep a proportion between the hand and the robot arm, Stäubli RX-90, used in the Robotics Lab of the IOC.

3. General scheme of the system

The whole physical system of MA-I can be divided in three main blocks: a Control PC, a Power Stage, and the mechanical hand itself (figure 2).

The Control PC (Pentium III, 700 MHz, 128 MB RAM, running under QNX-RTOS) is used for control purpose as well as for the Graphic User Interfase (GUI). Real Time requirements are needed to assure the control action every sample time. The PC is geared with 4 commercial I/O cards, PMDI MFIO-4A I/O, racked on a PCI bus. The electronics are synchronized with a programmable timer on one of the PMDI cards that is used as master. The timer generates an interruption signal for the PC and for the four cards with a period of 1 ms. (sampling period). Each PMDI card has four blocks, each block reads the signal of an incremental encoder assembled with each motor. The actual joint position is incrementally computed from the encoder signal. The output of each block is an analogue signal (± 10V) that acts as a control signal input to the Power Stage. Each card block also reads 2 digital inputs, used to watch out for the status of the two end stroke switches that indicate the minimum and maximum displacements allowed in each DOF. These signals are used as protection for the mechanical system and as a position reference at the system start up. (maximum and minimum position of each articulation). The PC is also in charge of interacting with the robot controller.

The Power Stage is power electronics equipment that turns the voltage from the control signal generated in the PC into proportional current on the DC motor. Basically this block is in charge of:

- Amplify the control signal.
- Protect DC motors against over current.
- Group in ribbon cables the different signals going and coming from the mechanical hand to the PC (there are 172 wires that transmit digital and analog information, like the end stroke states, the encoder pulses and the control signals for each DOF).

Finally, the third block is the mechanical hand itself, and will be described in the following sections.

Regarding the general operation of the system, the user defines, throught the GUI in the PC, the desired position of each fingertip or, directly, the position of each joint of the hand. If the fingertips are specified, the system finds the final position of each joint by solving the hand inverse kinematics. With the desired and the actual positions, a position vs. time profile is built for each joint assuring that the set points do not violate the system capabilities (e.g. maximum acceleration) and that all the joints arrive at the same time to the desired position. From these profiles, lists of position set points are generated, which are fed, in a FIFO style, to the control laws of the articulations at every sampling period. The control laws generate the control signals that are transmitted to the Power Stage through the specific I/O cards. The power stage transforms the control signals into current for the DC motors in the hand. Additional information about the whole system can be found in [3] and [11].

4. MA-I Kinematics

MA-I has four appendages, three fingers (anular, heart and index) and a thumb (hereupon sometimes referred to as "fingers"). The reduction of one finger with respect to the human hand was due to a cost-

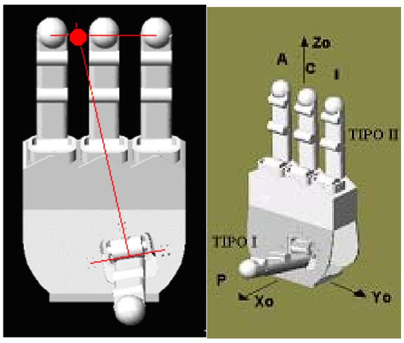


Figure 3. Placement of the finger bases.

benefit analysis, as the fifth finger on the human hand adds only five percent to the total dexterity of the hand.

The fingers and the thumb only differ on the dimensions of the phalanges, the thumb having larger phalanges. The bases of the four fingers are placed on a flat surface, the palm. The base of the thumb lays nearly a fourth of the total width of the palm away from its middle line. The bases of the other three fingers are aligned on the extreme of the palm. Figure 3 illustrates the hand structure.

All four fingers have 4 DOF with exactly the same DOF arrangement: two single rotational DOF between the three phalanges of the finger (the distal and medium articulations), and another two orthogonal rotational DOF at the base of the finger (the proximal articulation). This arrangement enables the extension and flexion of each phalange and the abduction and adduction of the whole finger. Figure 4 shows the configuration and orientation of the DOF in each finger. Something to be pointed out is the special mechanical arrangement in the proximal articulation (described in section 5), used to obtain two orthogonal rotational DOF with the axis of rotation lying in the same plane.

Three additional “virtual” DOF are considered on the fingertip. Although they do not describe any real mechanical movement, these virtual DOF describe the contact point on the spherical surface of the fingertips

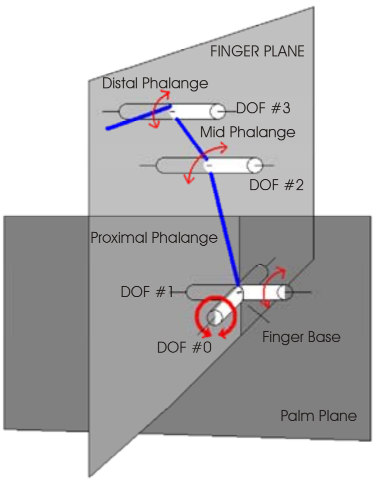


Figure 4. Arrangement of the finger DOF.

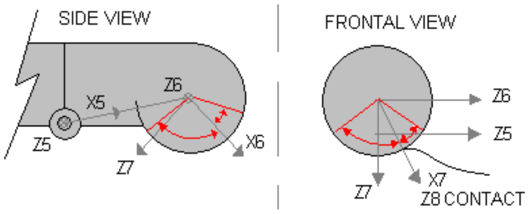


Figure 5. Virtual DOF at the fingertips.

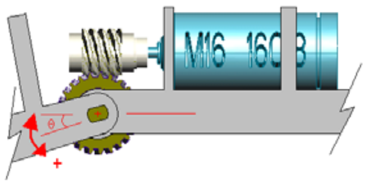
with respect to the end of the last phalange as it is shown in figure 5.

The D-H parameters that describe the kinematics of MA-I are listed in Appendix A.

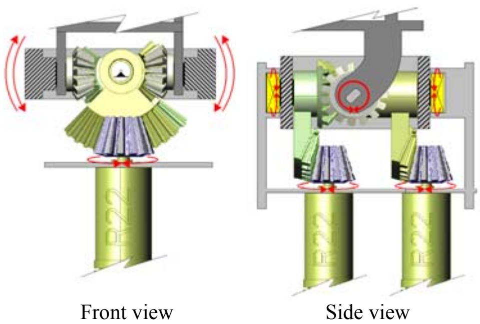
5. Mechanical features

MA-I has human shape but its size, 36 cm high and 25 cm width, doubles an adult human hand, and its weight is nearly 4 Kg. Each phalange is a lightweight machined aluminium structure, that, in the case of the medium and proximal phalanges, holds the DC motor that actuates the articulation, and in the case of the distal phalange supports the interchangeable fingertips.

The distal and medium articulations (one DOF each one) consist of a worm-gear transmission powered by a DC motor through a reduction gearbox (figure 6a). The proximal articulation (two DOF) is a special gear assembly allowing two axis of rotation to lie in the same plane. In this case, two DC motors, through their gearboxes, simultaneously move the two rotational DOF. If the two DC motors rotate in the same direction the articulation will rotate producing abduction or adduction movements, but if the two DC motors rotate in opposite directions the articulation will produce



a) Single DOF articulation



b) Double DOF articulation

Figure 6. Joint actuators.

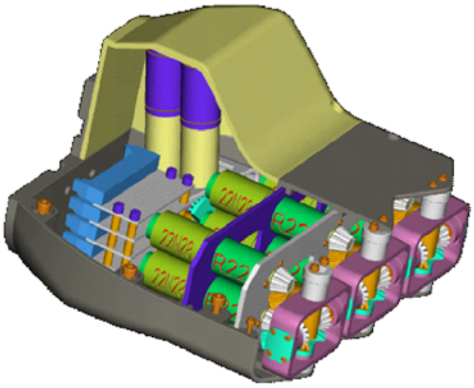


Figure 7. Motors of the proximal articulations cased in the palm.

flexion or extension movements (figure 6b). The eight DC motors (two for the proximal articulation of each finger) are located inside the palm (figure 7).

6. Software scheme

Modularity was the principal design priority for the software. Basically, there is a mainfraim that is in charge of some basic actions (like memory management, restoring the system when the program is shutdown or control of the I/O card drivers). It is also in charge of the creation of the following three specific processes (linking and initialising them):

- The Graphic User Interface (GUI).
- The low-level position planner (pathplanner).
- The controller.

The first two processes, GUI and pathplanner, communicate with each other through a shared memory, using a semaphore strategy to prevent the corruption of information during the read and write operations. The pathplanner communicates with the control process using a FIFO list.

All the software was programmed in C language using real time features of QNX (e.g. sleeping processes and priority management) to assure that the control process works correctly guaranteeing the correct input and output of information as well as the correct timing of the control loop.

The GUI allows the user to introduce the desired final position of the fingertips (i.e. the contact points) or directly to introduce the desired final position of each articulation. In the first case, the system solves the inverse kinematics of the hand to obtain the final position of each articulation. This information is passed to the pathplanner using the shared memory. The pathplanner builds a velocity profile for each articulation using the maximum velocity and maximum acceleration. From the 16 calculated profiles, the time needed by the slowest articulation is selected as the reference time for the computation of new profiles for

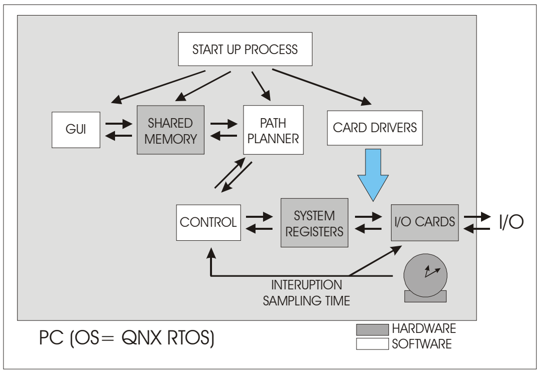


Figure 8. Software scheme

the other articulations in such a way that all the joints arrive to the desired position at the same time. The 16 velocity profiles obtained in this way are used to compute position paths that provide a position setpoint for each sampling period. This segmentation of the final paths generates 16 FIFO lists that are the inputs to the control process.

The control process has three mayor tasks: watch out for the end-stroke switches to protect the mechanical hardware, initialise the position of each articulation by moving the fingers up to an extreme of their ranges and use this position as a reference for the incremental encoders (home procedure), and calculate and update the control action for the 16 control loops. Figure 8 shows a general layout of the software scheme. The control system is explained in the next section.

7. Control System

The control system of MA-I contains 16 position control loops, independently controlling each of the 16 DC motors. In the case of the proximal articulation, that has 2 DOF and is actuated by 2 motors with synchronize movements, the synchronization is done at the time of the determination of the set points for each motor, that are then controlled by independent control loops. Sampling period is 1 ms for all the position control loops. Force control using force sensors at the fingertips is under development.

The finger articulations were modelled considering a classical DC motor model, the stiction and Coulomb friction forces (that significatively affect the system), and the saturation of the Power Stage amplifiers (that limit the acceleration-velocity working range). The complete model is non-linear, but a second order linear model was obtained by linearization. The parameters of the model that could not be obtained from the data provided by the motor manufacturer (SCAP) were obtained experimentally. Different tests were performed on the real system and on the model in order to do a final adjustement of the parameters so that the model best fits the system behaviour.

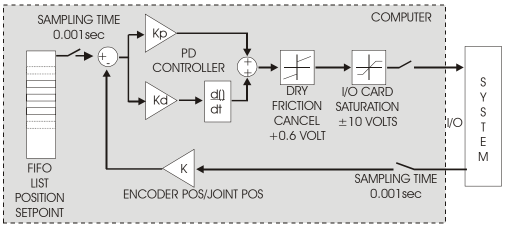


Figure 9. Control scheme.

The linear model was used for the design of a PD controller. A feedfoward friction force compensation was added to the PD controller and then it was tested and tunned with the complete non-linear model before being applied to the real plant. Figure 9 shows the control scheme, and figure 10 shows real data results obtained from one of the proximal articulations (the figure shows the setpoint and the real position close to it along the time, as well as the current on the DC motor).

8. Conclusions and Future Work

The mechanical hand MA-I designed and built at IOC-UPC has been described. Figure 11 shows the MA-I hand coupled to an industrial robot Stäubli RX-90. The main features of the MA-I system can be summarized as follows:

- Anthropomorphic: 4 fingers, 4 DOF each finger.
- Mechanically self-contained: easy coupling-decoupling with any robot arm.
- Modular: different sensors can be added, different control strategies can be tested.
- Real time operating system (QNX) to assure control performance.

Open topics currently under development are:

- Implementation of fingertips with force sensors.
- Implementation of force control with force feedback from the fingertips.
- Implementation of more friendly and general GUI.

Future works related with MA-I are:

- Teleoperation using a sensorized globe with haptic capabilities.
- Teleoperation using a graphic simulator of the hand-arm ensamble (already developed).
- Inclusion of vision feedback in the teleoperation.

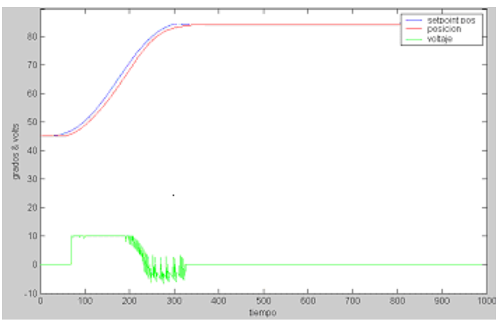


Figure 10. Example of the control system behaviour.

Figure 11. MA-I coupled to an industrial robot Stäubli RX-90

Appendix A. D-H Parameters for MA-I

Table 1 describes the D-H parameters for MA-I. The joint described by i=1 is a virtual one representing a constant tranformation whose porpose is to facilitate the coupling of the D-H parameters of the hand with the D-H parameters of any robot arm. In this way, the D-H parameters of the first real joint of each finger of the hand are related to a fixed point in the hand and are independent of the D-H parameters of the robot arm. The group of parameters given by i=2,..,5 are the real DOFs of the hand articulations, and the parameters given by i=6,…,8 are the virtual DOFs used to define the contact point on the fingertip surface.

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Table 1. D-H parameters of the hand MA-I

i	a_{i-1}	α_{i-1}	d_i	θ_{i-1} RANGE
1	0	0	197.55	+90 (constant)
2	-67	90	9.5	+78 / -102
3	0	90	0	-7.5 / +82.5
4	76.66	0	0	+52.5 / +97.5
5	56	0	0	-16.65 / +73.35
6	33.62	0	0	+20 / +135
7	0	-90	0	+45 / - 45
8	20	0	0	0 (constant)

D-H Parameters: Base – Annular.

i	a_{i-1}	α_{i-1}	d_i	θ_{i-1} RANGE
1	0	0	197.55	+90 (constant)
2	0	90	9.5	+78 / -102
3	0	90	0	-7.5 / +82.5
4	76.66	0	0	+52.5 / +97.5
5	56	0	0	-16.65 / +73.35
6	33.62	0	0	+20 / +135
7	0	-90	0	+45 / - 45
8	20	0	0	0 (constant)

D-H Parameters: Base – Heart.

i	a_{i-1}	α_{i-1}	d_i	θ_{i-1} RANGE
1	0	0	197.55	+90 (constant)
2	67	90	9.5	+78 / -102
3	0	90	0	-7.5 / +82.5
4	76.66	0	0	+52.5 / +97.5
5	56	0	0	-16.65 / +73.35
6	33.62	0	0	+20 / +135
7	0	-90	0	+45 / - 45
8	20	0	0	0 (constant)

D-H Parameters: Base – Index.

i	a_{i-1}	α_{i-1}	d_i	θ_{i-1} RANGE
1	0	0	264	-44.56 (constant)
2	7.56	14.11	-203.32	+33.44 / -57.44
3	0	90	0	-7.5 / +82.5
4	76.66	0	0	+32.5 / +97.5
5	66	0	0	-12.73 / +77.27
6	39.17	0	0	+20 / +135
7	0	-90	0	+45 / - 45
8	20	0	0	0 (constant)

D-H Parameters: Base – Thumb.