Fuzzy Enhanced Control of an Underactuated Finger Using Tactile and Position Sensors*

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***Abstract*— This paper proposes a control scheme dedicated to underactuated fingers with the intention of maximizing the capabilities of the latter using tactile and position information at a minimum cost. Tactile sensors are implemented on one prototype of underactuated finger and used to enhance the behaviour of the hand despite its limited number of control signals. First, tactile technology is briefly recalled and discussed. Second, the electronic design of the sensors' controller is presented. Third, a real-time control scheme is introduced, based on a fuzzy force control method. Finally, a slippage prevention technique is presented. Results are discussed based on experimental observations and indicate that the behaviour of underactuated fingers can be substantially enhanced with tactile information and a classic fuzzy control approach.**

***Index Terms*— Grasping, underactuated finger, tactile sensors, fuzzy logic.**

I. Introduction

Significant efforts have been made to find designs of robotic hands that are simple enough to be easily built and controlled in order to obtain practical systems [1], particularly in human prosthetics. The lack of success of these complex devices is mainly due to the cost of the control architecture needed with often more than ten actuators plus many sensors. In order to overcome these limitations, a particular emphasis has been placed on the reduction of the number of degrees of freedom, thereby decreasing the number of actuators. In particular, the SSL hand [2], the DIES-DIEM hand [3], and the TBM hand [4] have followed this path. On the other hand, few prototypes involve a smaller number of actuators without decreasing the number of degrees of freedom.This approach, referred to as *underactuation* can be implemented through the use of passive elements leading to a mechanical adaptation of the finger to the shape of the object to be grasped [5], [6], [7]. The idea of aiming at the spatial complement of the shape of an object to ensure a distributed grasp is rather common in biologically-inspired robotics: e.g. snake robots or elephant trunks.

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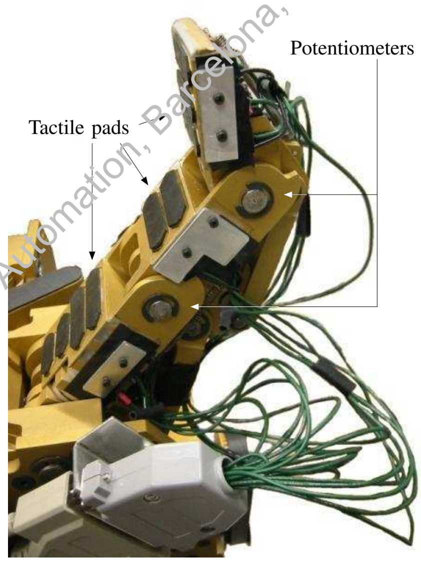

Fig. 1
MARS'S FINGER EQUIPED WITH TACTILE SENSORS.

II. Tactile Sensors

In this work, one of the MARS [8] prototype finger's phalanges (Fig. 1) have been equipped with Force Sensing Resistors (FSR): three for the proximal phalanx, two for the indermediate phalanx, and three for the distal phalanx, to allow experimental testing of the added value of tactile sensing to control underactuated hands. This finger has only one motor to close and open the three phalanges. Shape adaptation is provided by means of springs and mechanical limits [7]. Tactile sensors are devices providing pressure data and often surficial distribution of the latter on the sensors, i.e. localization. These sensors are intended to give robots the sense of touch and generally use matricial technology. Such devices have numerous applications for robotic hands [9], [10], [11], [12]: slippage detection, friction coefficient estimation, vibration detection, internal efforts control, contact geometry estimation, grasp stability enhancement, mechanical impedance control, etc. However, tactile sensors have been reported to be prone to noise and to have limited range of measure. This paper proposes to discuss their application to underactuated hands, and to verify if the global behaviour of the hand can be enhanced with tactile information. The limited amount of control available over the behaviour of the hand is penalizing from a control point of view. Nevertheless, with additional sensors, one can try to make the control more intelligent without becoming too complicated. Indeed, the complexity of controling multifingered fully actuated robotic hands, is usually linked to the number of actuators required.

A very interesting survey of tactile sensing is presented in [13], in which some explanations are provided for the lack of success of the tactile sensors despite the general opinion of the researchers in the late 80's. Interestingly enough, despite the long list of failures of the tactile sensors presented in the latter paper, the author remains confident that tactile sensors will be of increased use in robotics, especially medical and service robotics. The Interlink Electronics Force Sensing Resistors (FSR) are consituted by single cells of a polymer thick film which exhibits a decrease in resistance with an increase in the force applied to the active surface. These devices are quite cheap (less than four US$/piece) and small enough to fit in an underactuated finger. With the intention of performing preliminary experiments with tactile sensing, they were chosen as a good compromise between price and performance. This paper intends to illustrate the use of FSR as elements of a tactile array with a limited amount of sensors and used to measure/control the grasp force values and also to detect/prevent slippage. The only particularity that differentiates an underactuated finger from the previous tactile experiments is that one does not have the freedom of movement available in other robotic hands. Indeed, underactuated hands can only press harder or lighter, but independent motion or force control of the phalanges is impossible. It is important to note that since the hand is not fully actuated, changes between the ratios of the contact forces on the different phalanges cannot be controlled. This is particularily penalizing since the equations of the contact forces, established in [16], show that typical variations on the contact force generated by the finger on the object are from 1 to 20 depending on the contact locations and the finger geometry.

III. Controller Design

Using Force Sensing Resistors (FSR), the first step is to translate the variation of resistance of the sensor into a voltage that can be acquired and processed using a digital acquisition board on a standard PC computer. This is referred to as the "tactile data inversion" problem. Our choice has been an inverting operational amplifier circuit presented in Fig. 2.

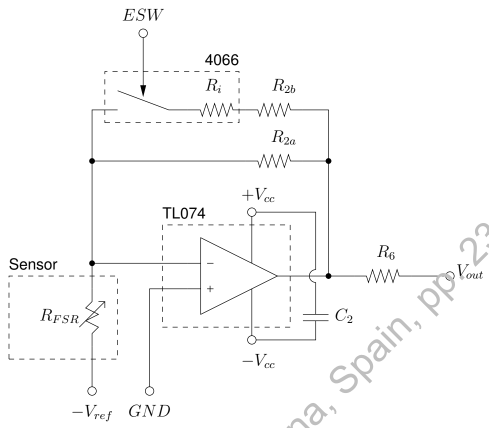

Fig. 2
Basic circuit cell.

The circuit presents the addition of another feedback resistor (R_{2b}) with an analog switch provided by a CMOS 4066 chip. This allows to switch the gain of the amplifier between two predefined values. Indeed, by using such a circuit, one maps the $0 - V_{cc}$ voltage delivered by the amplifier to two different ranges of pressure values. For instance, to map the voltage to approximately either $0{-}2$ kg or $0{-}10$ kg, as in our case. Thus, the sensitivity is improved for light duty grasps, which correspond to less than 2 kg maximal forces. The three phalanges do not have the same resistor values: this choice has been made in order to enhance even more the sensitivity of the last phalanx of the finger. According to the results presented in [16] and previous practical experiments, the contact force on the last phalanx of the finger is always much smaller than the force on the first one. Also note that two potentiometers allowing to measure the angles between the phalanges have also been connected to the controller board, using a non-inverting circuit. In the FSR case, the resistor is expected to be close to an inverse function of the payload applied (or the grasp force in our case). Therefore, an inverting circuit is particularly well suited for this task. Furthermore, one could use the negative power supply needed by the amplifier to provide a steady V_{ref}. Using the double gain circuit previously presented, one obtains:

$$V_{out} = \frac{R_{2a}(R_{2b} + R_i)}{R_{FSR}(R_{2a} + \mu R_{2b} + R_i)} V_{cc} \tag{1}$$

with

$$\begin{cases} \mu = 1 & \text{if analog switch is closed} \\ \mu = 0 & \text{otherwise} \end{cases} \tag{2}$$

where R_i is the internal resistance of the analog switch (we used Motorola MC14066B chip with a typical resistance of 1050 Ω) and R_{FSR} is the resistance of the FSR. The resulting board behaves very well in practice and noise on the measure is acceptable in the whole frequency spectrum.

Digital filters have also been used to process the data. In our case, digital fourth order elliptic filters have been designed, allowing a lag time typically inferior to 20 ms. Such a filter cancels most of the noise while preserving the ability to recognize short-duration phenomena like slippage (cf. Section IV-C).

RT-Lab^{TM} from Opal-RT is a software technology dedicated to real-time control enabling model separation to allow distributed execution, while automatically generating, downloading, and running real-time, distributed simulation software code.

IV. Experimentation

A. Calibration

Experimental calibration has allowed to establish a practical relationship between the resistance of the FSR and the load applied. An illustration of the data collected is presented in Fig. 3, along with a curve fitted to this data. The curve has the form:

$$F = \frac{p_1}{R_{FSR} + q_1} \tag{3}$$

where F is the load applied in kg, R_{FSR} is the FSR resistance in kΩ, and p_1 and q_1 are the curve fitting variables. Numerical results of a least-square optimization curve fitting are:

$$\begin{cases} p_1 = 0.89, \;\; q_1 = -1.18 \text{ for the distal phalanx} \\ p_1 = 6.95, \;\; q_1 = -4.51 \text{ otherwise} \end{cases} \tag{4}$$

Both sets of values achieve a R-square confidence score superior to 0.9 (the closer to 1, the better): 0.99 for the proximal and intermediate phalanges, 0.91 for the distal phalanx. Therefore, one can write a relationship between the applied load and the output voltage of the board:

$$F = G\frac{p_1 V_{out}}{q_1 V_{out} + R_2 V_{cc}} \tag{5}$$

where G is an ajustable gain used for the fine tuning (ideal value is 1) of each FSR independently and with:

$$\begin{cases} R_2 = \frac{R_{2a}(R_{2b}+R_i)}{R_{2a}+R_{2b}+R_i} & \text{in power grasps } (\mu = 1) \\ R_2 = R_{2a} & \text{in precision grasps } (\mu = 0) \end{cases} \tag{6}$$

Note that (5) should be used preferably over (3) and (1) for better numerical accuracy. Once the preliminary task of calibration is completed, one shall proceed with experiments using the tactile feedback. Two research directions have been investigated: force control, and slippage detection.

B. Force Control

Preliminary experiments have been conducted in force control to ensure that the grasping force can be controlled using tactile feedback. However, experimental results prove to be very disappointing. Maintaining the grasping force in the neighbourhood of the command is very difficult with a simple force control scheme, using a PID for instance. Experimental results indicate that this is mainly

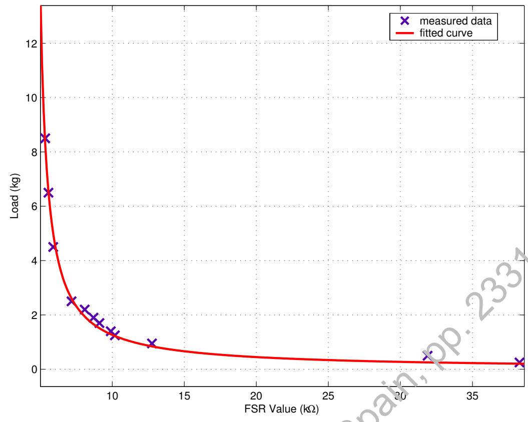

Fig. 3
IDENTIFICATION DATA.

due to the friction in the joints that make the actuation almost non-backdrivable. In other words, the grasp forces cannot be easilly decreased. After a closing sequence, if the actuation torque becomes zero, the grasping force is not zero as it should be, but typically almost 50% of its previous value. In practical terms, that means that even by stopping the actuator, the finger will continue to grasp the object. The phalanx forces are not sufficient to counter the friction in the joints, thus forces are applied but no motion is produced. In fact, firm grasps can be achieved with the actuator turned off. Therefore, if one wants to finely tune the grasp force, one must develop other more advanced control schemes dedicated to manage large friction. Two different approaches are possible to overcome this problem: e.g. either a friction compensation scheme or an intelligent control scheme. Friction compensation is not very attractive since it requires precise friction modeling which depends on the seized object. An intelligent control approach seems more promising, like for instance sliding mode or fuzzy logic. This is when tactile sensing can be of the uttermost importance: by using these sensors one can have a closed-loop force control scheme and for example, detect if the grasping forces are on the edge of vanishing, and then, resume the grasping actuation.

Hence—and since PID control has been proven unsatisfactory—a fuzzy logic [17] approach has been taken. In our case, the rationale for controlling the finger using fuzzy logic is to increase/decrease the actuator torque, hence the contact force, until the objective contact force is attained. Using the variation of the actuator torque as the output of the controller and not the torque value itself as in [18], one achieves more flexible adaptability. Furthermore, experimentations have shown that the actuator torque required in order to satisfy a prescribed grasping force can vary significantly. Indeed, as shown in [16], the contact forces are highly sensitive functions of the configuration (joint angles) of the finger and the contact locations on the phalanges. The input of our fuzzy controller is then the contact force error while its output is the actuator torque variation. The fuzzy error force is defined as

$$\epsilon_F(t) = F_d(t) - F_m(t) \tag{7}$$

where F_d is the desired total grasping force and F_m is the measured grasping force evaluated as the moving average on four values of the absolute total error measures, i.e.

$$F_m(t) = \sum_{k=0}^{3} \frac{1}{4} \sqrt{\left(\sum_{i=1}^{9} F_i(t - k\Delta t) \right)^2} \tag{8}$$

where Δt is the sampling period (1 ms with our prototype), and $F_i,\ i = 1..9$ are the forces measured by the FSR. It is noted that the full 1 KHz sampling frequency has been used for both the actuator control loop (fuzzy and lower level) and the force/position data acquisition. The fuzzy membership functions associated with the force error are illustrated in Fig. 4.

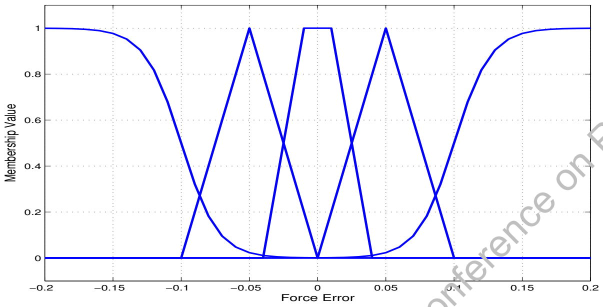

Fig. 4

MEMBERSHIP FUNCTIONS OF THE FORCE ERROR.

Initial experiments showed that these rules are not sufficient, since the contact force tends to oscillate around the desired input. This oscillation creates the impression that the finger is "palpating" the object. A solution to prevent this phenomenon is to add another fuzzy input, namely the measured force derivative, to slow down the grasping force increase (or decrease) when the error force is small, i.e. add some damping to the system, but not always. The PID controller did not allow such finesse. The force derivative dF is defined as the moving average on fifty values of the total phalanx forces, i.e.

$$dF(t) = \sum_{k=0}^{49} \frac{1}{50} \frac{d}{dt} \left(\sum_{i=1}^{9} F_i(t - k\Delta t) \right) \tag{9}$$

The resulting fuzzy control surface itself is illustrated in Fig. 5. The minimum function has been associated to the fuzzy "and" operator while a centroid defuzzification

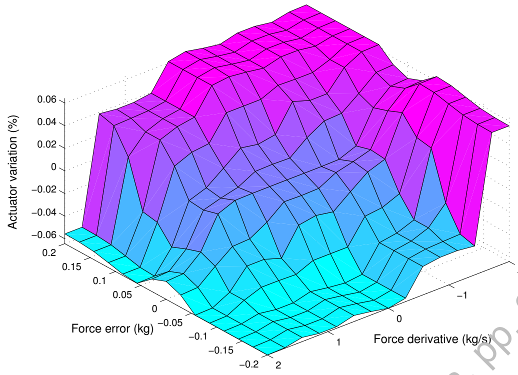

Fig. 5

FUZZY CONTROL SURFACE.

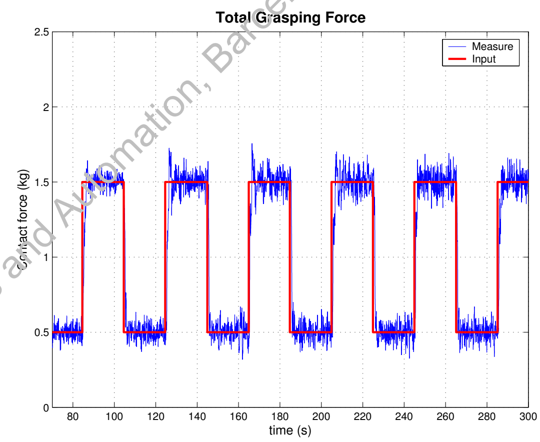

Fig. 6

FUZZY FORCE CONTROL EXPERIMENTAL DATA.

method has been chosen. A typical example of force control result is presented in Fig. 6: the oscillations have been considerably attenuated. A square wave input has been chosen to illustrate the repeatability of the experiments, as well as the similar behaviour during increase and decrease of the command. However, it has been experimentally found that some oscillations may transitorily subsist in the case of compliant contacts, i.e. locally deformable objects. Nevertheless, the latter can be eliminated by increasing the damping of the controller, without a significant decrease of the settling time since the damping only acts when the error is small.

C. Slippage Detection and Prevention

To begin with, slippage detection *should* not be possible with the kind of sensors we use. Indeed, the FSR can only measure pure normal forces, no tangential information of any kind is theoretically available. However, slippage can be detected as it has been concluded experimentally. One can note a very significant variation in the normal

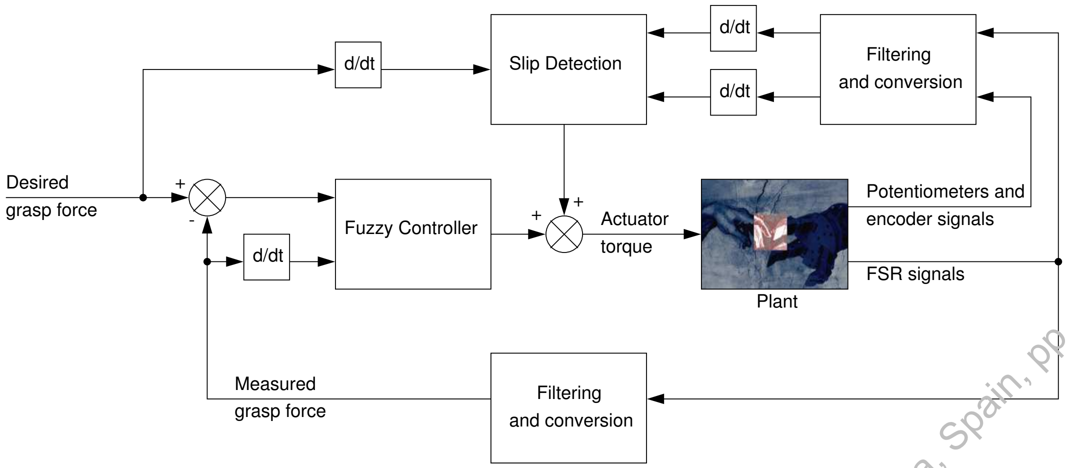

Fig. 8
CONTROL SCHEME OF THE FINGER.

force value when slippage occurs, a similar result has been reported in [19]. This variation comes without any motion of the finger itself which is thus still grasping what appears to be a motionless object. Furthermore, no change in actuator torque has been requested. Thus one has the situation of a motionless object, grasped with a constant actuator torque but the tactile sense of the hand records a quick decrease of the force applied. This phenomenon can only be explained either by a local deformation of the object or by slipping. Both cases require a different handling. For instance if the object is locally starting to deform, that means that the object is breaking down, the grasp forces should therefore be decreased. On the contrary, if the object is slipping, grasp forces should be increased to prevent the object from escaping. In fact this dilemma is not solvable without *a priori* knowledge or extra information. From an experimental point of view, slippage is detectable, even with cheap, off-the-shelf sensors like FSR. However, a 100% success rate can not be ensured, and may depend on the material combination. An example of slippage with a power grasp is illustrated in Fig. 7, similar results are found with pinching precision grasps. Note that the sensors' values are usually not the same before and after the slippage. The event "slippage" has been described as corresponding to: a short-time variation the phalanx forces, a constant actuation torque, no motion of the finger. To detect the motion of the finger, one has to use the data provided by the potentiometers and the actuator's encoder. Indeed, the latter is not sufficient to detect a motion of the finger since the finger can move with its actuator locked: this feature is mandatory to obtain the shape adaptation behaviour. In response to this event, an anti-slippage scheme has been implemented that increases the actuation torque as soon as these characteristic conditions are fulfilled. The magnitude of the increase has been experimentally determined to be a jerk increase of 10%, mimicking the reflex action of a human being, and is added to the force control component of the command. This superposition of the commands has also been reported to be the principle behind human prehension [20]. Since both commands are to be added, the influence of the fuzzy force controller should be taken into account. Indeed, the force controller detects the decrease of the grasping force and tries to counter the latter. The fuzzy force controller is however too slow to actually prevent slippage. An illustration of the complete control scheme is presented in Fig. 8.

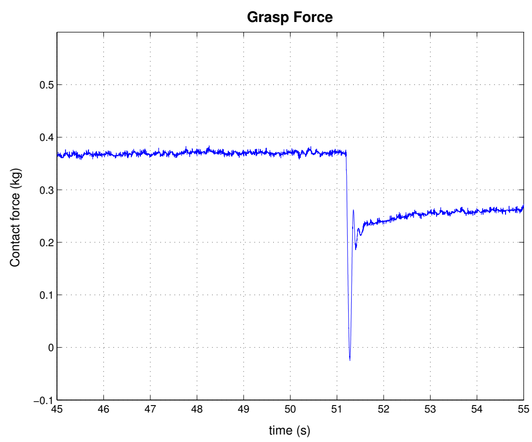

Fig. 7
TYPICAL SENSOR OUTPUT DURING A SLIPPAGE (CYLINDRICAL POWER GRASP, FILTERING ACTIVE).

V. CONCLUSIONS

To conclude this paper, it can be noted that promising experiments have been conducted with tactile sensors on

TABLE I

HARDWARE COSTS.

Item	Units	Price (US$)
FSR	8	28
DB cables	3	40
electronic board	1	15
components (IC, resistors, etc.)	-	20
power supply	1	20
Total		≤ 125

an underactuated finger and yes, the behaviour of underactuated fingers can be substantially enhanced with tactile information. Underactuated fingers may even be a predilection type of hands for the use of tactile sensing since the simplicity of the initial controller leaves significant computation time to process the tactile data in real-time. However, the use of tactile sensing with underactuated fingers has rarely been reported [14], [15].

Experimental force control has been implemented with very good results using a fuzzy logic controller with sufficient finess to hold an egg together with a person and move it with a pinch grasp (cf. Fig.9). It should be noted that this hand was designed for industrial applications and can lift more than 70 kg, much more than what is required to crush the egg. Prevention of slippage has been built on top of the previous controller. One should note that the total cost of the hardware required to achieve this intelligent behaviour (see Table I) is very limited and negligible compared to the machining cost of a finger. Another aspect that can be of interest and has not yet been investigated is object recognition using tactile sensor data.

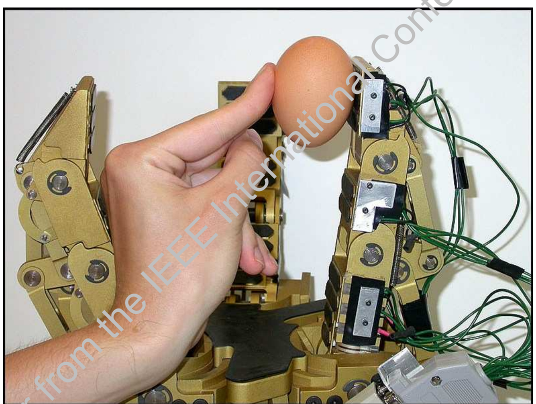

Fig. 9

FORCE CONTROL EXPERIMENT: HOLDING AN EGG IN COLLABORATION.

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