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Sensitive Manipulation

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Sensitive Manipulation

by

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Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

This thesis presents an effective alternative to the traditional approach to robotic manipulation. In our approach, manipulation is mainly guided by tactile feedback as opposed to vision. The motivation comes from the fact that manipulating an object implies coming in contact with it, consequently, directly sensing physical contact seems more important than vision to control the interaction of the object and the robot. In this work, the traditional approach of a highly precise arm and vision system controlled by a model-based architecture is replaced by one that uses a low mechanical impedance arm with dense tactile sensing and exploration capabilities run by a behavior-based architecture.

The robot OBRERO has been built to implement this approach. New tactile sensing technology has been developed and mounted on the robot's hand. These sensors are biologically inspired and present more adequate features for manipulation than those of state of the art tactile sensors. The robot's limb was built with compliant actuators, which present low mechanical impedance, to make the interaction between the robot and the environment safer than that of a traditional high-stiffness arm. A new actuator was created to fit in the hand size constraints. The reduced precision of OBRERO's limb is compensated by the capability of exploration given by the tactile sensors, actuators and the software architecture.

The success of this approach is shown by picking up objects in an unmodelled environment. This task, simple for humans, has been a challenge for robots. The robot can deal with new, unmodelled objects. OBRERO can come gently in contact, explore, lift, and place the object in a different location. It can also detect slippage and external forces acting on an object while it is held. Each one of these steps are done by using tactile feedback. This task can be done with very light objects with no fixtures and on slippery surfaces.

Thesis Supervisor: Rodney Brooks
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Chapter 1

Introduction

1.1 Motivation

Current industrial robots are capable of executing many complex manipulation tasks, for example, robots assemble car's parts, such as bodies and engines, with high precision and speed. This is possible because the production line has been carefully engineered to make the robots perform successfully. For instance, the lighting and the placement of objects relative to the sensors are controlled, and the perception is specialized and model-based. However, these robots do not perform as well in slightly less controlled environments as the one at the beginning of the production line. Here, parts have to be picked up and placed in the right position for the robots to work. This task, known as bin picking, is simple for human workers but it is still an open problem for factory robots. If the environment is even less engineered, as is the case in a living room or a kitchen, these robots are not capable of dealing with the variable conditions. Tasks such as manipulating objects with different properties which have not been previously modelled become unfeasible.

Robots can perform more sophisticated tasks when they are teleoperated. For example, teleoperated humanoid robots have performed tasks, such as grasping everyday objects, using a power drill, throwing away trash, and retrieving a drink from a refrigerator. However, teleoperation is slow and demands significant effort on the part of the human operator. This is more noticeable in the robots exploring Mars where

simple tasks such as placing a probe in a rock can take a long period of time (about a day). Moreover, some tasks even on Earth are not feasible due to communication delays. Such is the case of adjusting the grip when lifting an object. This is because by the time the teleoperator detects the slippage of the object, this has already fallen and the command sent to adjust the grip is useless.

Humans are much more adaptable. We observe people doing many dexterous tasks with their limbs. For instance, picking up a new object in a dynamic environment is not at problem for us. Because of this high performance, we look for inspiration in human manipulation to build robots capable of manipulating objects in poorly modelled environments.

It is believed that we use many sensory inputs to manipulate objects successfully. Visual input has been considered of paramount importance, therefore, most of the work done in robotic manipulation has taken this direction. That is, manipulation guided by vision. This approach has taken us to the current state of art in robotic manipulation.

However, one can easily think of examples where direct visual input is not used for manipulating object. Imagine, for example, waking up in your bedroom at midnight, reaching for the remote control, reorienting it and turning on the TV. All these steps were done in darkness. The complete task can be executed due to the information provided by the sensors located in the hand and arm. This information permits us to safely explore the environment, extract features to identify objects and control the interaction hand/arm/world. Moreover, experiments performed by Klatzky et al [61] have shown that blindfolded individuals were capable of identifying objects using only their hands with an accuracy of 96%. The dextrous manipulation performed by blind people is even more impressive.

Therefore, we think that tactile sensing is an specially appropriate sensing modality given that manipulation fundamentally relies on the contact between the robot and the world.

Information such as location(s) of contact, local shape of an object, and slippage are some of the parameters that tactile sensors could supply. These data would

facilitate making decisions about the motion of a hand while grasping an object or about the force applied while gripping an object to avoid slippage. Those are parameters directly related to the hand/object interaction that would be difficult to obtain in a timely manner using other sensing modalities. Even though obtaining information from the direct physical robot/world interaction seems so useful, if not necessary, its use in robotics research has not been generalized due to technological limitations.

It is important to note that given the nature of tactile sensing, it is useful to actively increase the chances of the sensors coming in contact with objects to extract information. That is, using the tactile sensors to explore the surroundings. We can observe this in animals and humans who use their limbs to actively explore their environment.

Up until this time, we have not seen robots exploring their environments in general. The main reason for that is the design of today's robots. They are designed to position their limbs precisely using only their proprioception feedback. To achieve this high precision, robots limbs have to have high stiffness. High stiffness is not ideal for exploration because if an object crosses the robot's trajectory unexpectedly, the robot will not stop and it will damage either itself or the object. It is true that the robot can have sensors that detect this collision and if the actuators were fast enough the robot could stop in a timely manner. In practice, at the moment of the collision, only the passive elements of the robot determine the response of the system. Because the robot is stiff the collision most likely will not be gentle to the robot or the object.

Human and animals have limbs whose stiffness can be controlled but in general this stiffness is lower than that of a robot. This makes it possible to explore their surroundings in a safe manner which helps to adapt to changes in the environment. Therefore, we consider that having low impedance limbs combined with tactile sensing will allow us to implement more flexible manipulation.

In this thesis, we approach manipulation as a task mainly guided by tactile and force sensing and we use vision as a complement. We call this approach *sensitive manipulation*. In this approach, manipulation is as much about action as it is about

perception and it is intrinsically responsive to the properties of the object being manipulated.

However, there are many challenges that need to be addressed to implement *sensitive manipulation*. Our solutions are presented on the following chapters.

1.2 The challenges

In this section we present some of the challenges that we faced while implementing *sensitive manipulation*. We briefly mention some of the solutions implemented in our robot OBRERO. Details of the robot are presented in chapter 2.

1.2.1 Contact vs Non-Contact sensors

Manipulating objects implies coming in contact with them. This is different from navigation, for example, where you want to avoid the obstacles and in general uses non-contact sensors (infrared, ultrasound and cameras). Non-contact sensors allow the robot to analyze the environment without greatly affecting it. In contrast, *sensitive manipulation* uses contact sensors (tactile and force sensors) to extract information. This means that a robotic limb, populated with contact sensors, should be capable of safely coming in contact with the environment to extract information using those sensors.

As mentioned earlier, traditional robots cannot safely come in contact with the environment because of their high stiffness.

In our approach, we deal with this challenge by building our robot with low mechanical impedance actuators. This feature allows the robot to safely come in contact with the environment which enables efficiently use contact sensors.

1.2.2 Coming in Contact with the object

The robot needs to come in contact with an object to interact with it. This event should be safe for the robot and the object since we do not want to damage either of

them. Although this might sound like a simple task it is not always simple to perform it.

Coming in contact with an object is a nonlinear problem from the point of view of the control of the arm [104]. It implies to move from position control to force control, from a non-constrained environment to a constrained one. In practice, a combination of position and force control is preferred. To understand this, let's consider the following example. An arm (position control) comes in contact with an object, at this moment transient forces known as impact forces are applied to the arm. The controller is then switched to force control. The impact forces can be large and make the controller unstable. Moreover, when the robot's arm comes in contact with the object and the control is switched to force control, the arm can bounce because of the elasticity of the impact or the object can move. This makes the arm lose contact again but its mode is in force control instead of position control. This produces an oscillatory behavior.

Therefore, a hybrid control that uses position and force combined (compliance) is more adequate to avoid the abrupt switching. A more detailed analysis about this topic and alternative solutions are presented in [104].

OBRERO uses two degrees of compliance to deal with this problem. These degrees of compliance are given by the actuators and by the tactile sensors.

1.2.3 Sensing the hand/object interaction

In order to control the interaction between the hand and the object we need to have sensors capable of detecting parameters related to that interaction. For example, contact, curvature, normal, sheer forces, motion, and slippage are a few. In humans and animals these sensors are in the skin.

However, a major problem in robotic manipulation has been the lack of tactile sensors that actually work beyond the laboratory bench. Many attempts have been made to create tactile sensors (see chapter 3) but in most of the cases the actual conditions present in a robot have not been considered [43]. Consequently, even detecting contact with an arbitrary object is not a solved problem nowadays. Moreover,

if we want the robot to manipulate objects, a useful property of a tactile sensor on a finger would be to deform in order to increase the contact surface with an object and as a consequence the friction.

The problem becomes a bit more complicated when the finger has low mechanical impedance. In this case the sensitivity of the sensor should be enough to detect the contact even when the fingers move due to their low impedance.

Certainly, alternative methods for detecting contact are available. For example, one method is to measure the torque on the proximal phalange of a finger using strain gauges instead of having surface sensors. This method works but the information that it can provide is limited. For example, more than one contact point or sheer forces cannot be detected.

As it will be described in more detail later, OBRERO uses a new kind of tactile sensor that provides information to detect contact from arbitrary directions, sheer forces, and rotational and linear slippage.

1.2.4 Using tactile data to guide motion

The traditional approach to manipulation models the interaction hand/object using an small number of contact points. At each contact point a normal force and a frictional cone are considered. This model makes the mathematics tractable.

However, in actual hand/object interactions this model does not always hold. For instance, the hand usually needs to have a flexible surface to distribute the pressure on the object. This is safe for the object because the stress on the contact surface is reduced. More importantly, a wider surface constrains the rotation of the object which is not usually considered in the model. If we include all these variables, obtaining a closed form expression will be complex.

In our approach, the robot hand has more points of contact with the hand and a wealth of information arises from the tactile and force sensors. Making sense of these data is definitely a challenge. Nevertheless, it opens the door to a greater understanding of the hand/object interaction.

Having a great number of data to make sense is a common scenario in artificial

intelligence and computer science. Such is the case of Computer Vision where an RGB image of 360 $\times$ 240 pixels, 8 bits resolution at 7.5 fps generates 15,552,000 bytes per second. For such amounts of data many analysis tools have been developed. Compared with those numbers, the tactile sensors of our current robot only generates about 1,600 bytes per second.

In chapter 5, we present some of the processing done with these data to extract information useful for the task, literally at hand.

1.3 The approach: sensitive manipulation

We approach manipulation as a task mainly guided by tactile and force sensing and we use vision as a complement. In this approach, we consider that embodiment and behavior-based architectures are important elements as discussed in the following sections.

1.3.1 Embodiment: The robot OBRERO

In simulation, robots have performed sophisticated manipulation tasks such as grasping convoluted objects, tying knots, carrying objects around complex obstacles, and extracting objects from entangled circumstances. The control algorithms for these demonstrations often employ search algorithms to find satisfactory solutions, such as a path to a goal state, or a set of contact points that maximize a measure of grasp quality. For example, many virtual robots use algorithms for motion planning that rapidly search for paths through a state space that models the kinematics and dynamics of the world. Almost all of these simulations ignore the robot's sensory systems and assume that the state of the world is known with certainty. For example, they often assume that the robot knows the 3D structure of the objects it is manipulating.

The results of such simulations are in few cases directly transferable to actual robots. The reason is that the models assumed in simulation to represent parameters such as friction, contact forces, etc., do not hold in the world beyond the simulation.

For instance, tactile sensors are generally not even modelled in simulations. In

cases in which they are considered, the contact points between the hand and the object are used as the tactile sensors readings. In actual robots, those contacts most likely will not be detected.

Brooks [13] has pointed out these problems and proposed embodiment as a solution that provides physical grounding. The physical grounding of the robot allows us to work with the actual data produced by the sensors and the actual actions executed by the actuators. Actual sensing and actuation determines in great part the kind of tasks that can be performed.

In the specific case of manipulation, embodied approaches have been limited by the current tactile sensing technology. To solve this problem we have developed tactile sensors (see chapter 3) that present helpful features for manipulation. These sensors have been tested in an embodied system: the robot OBRERO.

In our approach, we are capable of doing manipulation guided by tactile sensing because OBRERO has a body that provides information about the interaction with objects. Therefore, we consider embodiment of great importance to achieve *sensitive manipulation*.

1.3.2 Behavior-based architectures in manipulation

In order to achieve *sensitive manipulation*, we use a behavior-based architecture [1] that lets us deal with unknown environments. Traditionally, the trajectory of the robotic manipulator is completely planned based on a model of the world (usually a CAD model). This renders the manipulator incapable of operating in a changing environment (not to mention an unknown one) unless a model of the environment is acquired in real-time.

The same situation was already faced in mobile robotics and behavior-based architectures were introduced as a successful alternative. However, the transition to manipulation is not straight forward because of the nature of the variables involved. For instance, in a model-based approach the trajectory of the robot's limb is carefully planned and the hand only comes in contact with the environment in a carefully control manner. Unexpected contacts are generally dangerous and avoided.

If we now consider a behavior based approach, we can easily think of behaviors such as: move the finger following the surface of the object, move the hand until it makes contact with the object, or move the hand down to the bottom of the object while maintaining contact assuming the object is supported. All these behaviors rely on coming in contact with the environment.

Therefore, we believe that to take advantage of a behavior-based architecture in manipulation, the robot used should be capable of safely coming in contact with the environment and detecting this contact.

In the robot OBRERO, we use passive elements embedded in every actuator of the robot's limb. These actuators, known as series elastic actuators [88,111], make coming in contact with the environment safe. This makes it possible to use a behavior-based architecture on OBRERO.

1.4 Contributions

1.4.1 Overall contribution

The overall contribution is our approach to manipulation named ***sensitive manipulation***. Sensitive manipulation is about purposely guiding the motion of the robot's limb using mainly tactile information. In this approach, the robot's limb is not only an actuator device but also as a sensing device.

In this thesis we use sensitive manipulation to implement grasping. This implementation is enabled by the development of adequate technology also presented in this thesis.

To implement this approach the following points are considered important.

- The robot needs to have tactile sensors to extract information of the environment.
- The limb has to be compliant to gently interact with the environment. This compliance limits the precision of the limb in general but enables exploration.

- The capability of exploring together with the capability of sensing contact (dense tactile sensing) compensate for the lack of precision. For very many applications knowing that you are in contact with the object is more useful than precisely positioning the limb.

1.4.2 Technological contributions

Most robots are not dexterous in part because the technology needed is not available. In this thesis, we present five technological contributions to robotics manipulation. The first four enable the last contribution.

- The first is a new tactile sensing technology. This technology allows us to easily build **compliant tactile sensors** whose features are convenient for manipulation. Some of those features include: adequate shape to come in contact with objects, mechanical flexibility, high friction coefficient and high sensitivity.

- The second contribution is a new **scalable force actuator.** This actuator is designed to be cheap, easy to assemble, and easy to scale to small dimensions. This actuator operates with the same principle as a series elastic actuator. However, its mechanical simplicity enables its use in very constrained applications such as actuating a robotic hand.

- The third contribution is a new **force controlled robotic hand.** This hand has passive and active degrees of freedom and it can be controlled either using position or force control. Each one of its eight joints uses a version of the actuator above mentioned.

- The fourth contribution is an integrated platform named **OBRERO**. It integrates the tactile sensing technology, the actuators and the hand, mentioned above, with a force controlled arm and a head with two optical degrees of freedom (zoom and focus). The integration allows us to implement a behavior based approach to manipulation. OBRERO means human worker in Spanish.

- The fifth contribution is: the first humanoid robot that actually **integrates tactile information for guiding manipulation**. The robot is capable of coming in contact with an unknown object, use tactile feedback to move the hand around the object, and lift it. This integration is possible because of the first four contributions.

1.5 Road Map

This thesis is organized as follows. Chapter 2 presents the design and the implementation of the platform for *sensitive manipulation*, the robot named OBRERO. Especial attention is given to the robot's hand and its actuators. The tactile sensors used are presented in detail in chapter 3, where we cover the design, implementation and evaluation of these sensors. In chapter 4, we present some observations on humans that inspired part of this work.

An integrated system to approach manipulation using mainly tactile information is presented in chapter 5. The details of the different modules implemented as well as the integration are included. The chapter ends with the results obtained. *Sensitive manipulation* is contrasted with alternative approaches in chapter 6. In this chapter we also summarizes some of the lesson learned.

In chapter 7 we present alternative methods that learn about objects using sound and use shadows to estimate distances.

Chapter 2

OBRERO: A platform for Sensitive Manipulation

2.1 Introduction

In this chapter, we present the design, construction and evaluation of a humanoid platform (OBRERO) suitable for sensitive manipulation. The design of the platform is motivated by human manipulation. Humans are capable of manipulating objects in a dexterous way in unstructured environments. We use our limbs not only as pure actuators but also as active sensors. Human manipulation is so sensitive that many tasks can be accomplished using our hands without any help from vision. In contrast, humanoid robots in general are limited in the operations they can perform with their limbs alone.

However, if we consider tasks such as precise positioning or accurate repeated motion of an arm, we notice that, in general, humans are outperformed by robots because human limbs are clumsier than robotic ones. This apparent disadvantage is overcome by the great number of sensors and actuators present in human limbs which allows us to adapt to different conditions of the environment.

For instance, humans use their hands to touch or grab an object without damaging themselves or the object. This is possible because humans can control the force and the mechanical impedance exerted by their limbs when in contact with an object.

Robots, in general, cannot do this because their components lack the sensing and actuating capabilities needed to control these parameters i.e. force and impedance.

Moreover, the sensing capabilities of human limbs are not limited to force. Humans can also extract many features of an object they are holding [61] thanks to their highly innervated skin. In contrast, robotic limbs have a limited number of sensors, rendering them inadequate for feature extraction.

Motivated by these ideas, we have favored the sensing capabilities over the precision in the design of OBRERO's limb. The limb has force control, low mechanical impedance, as well as position and force sensing.

We use non-conventional actuators for the limb and dense tactile sensors for the hand (special attention is paid to the actuators in the hand because of size constrains). These actuators control the force and reduce the mechanical impedance. These features allow the limb to come in contact with objects in a safe manner. For instance, when contact occurs the platform needs to respond fast enough to avoid damaging itself or the object. In practice, when the limb comes in contact with an object, the passive elements of the system are the ones that determine the response. Therefore, these passive elements must have a low mechanical impedance to achieve contact compliance. This property is especially important when using the limb as an active exploring device.

While tactile information will dominate, *sensitive manipulation* also can benefit from visual and auditory perception. Such information will be used by the robot to improve the efficiency of manipulation, rather than be an essential prerequisite. Vision can give a quick estimate of an object's boundary or find interesting inhomogeneities to probe. Sound is also a very important clue used by humans to estimate the position of an object and to identify it. We have conducted experiments to take advantage of this fact in section 7.1 and [99]. The robot OBRERO has a 2 degree-of-freedom head that includes vision and sound. The camera has two optical degrees of freedom; focus and zoom. Focus is very useful to obtain depth information and zoom helps to obtain fine details of an image. The vision system will try to take advantage of natural cues present in the environment such as shadows, see section 7.2 and [36].

Figure 2-1: Robot OBRERO. The robot has a highly sensitive and force controlled hand, a force controlled arm and a camcorder as a head. OBRERO's hand has three fingers, 8 DOF, 5 motors, 8 force sensors, 10 position sensors and 160 tactile sensors.The head has 2 mechanical DOFs and 2 optical ones (Zoom and Focus).

This robot has been designed to approach manipulation using a behavior-based architecture [1]. A discussion for using behavior-based architecture is presented in section 1.3.2.

In this chapter we present the design and implementation of the robot OBRERO. A review of robotic platforms for manipulation is presented in section 2.2. The overall architecture of the robot is presented in section 2.2.1. The design and implementation of the hand and its actuation system are described in sections 2.2.3 and 2.2.2. The robotic arm and head are described in sections 2.2.4 and 2.2.5.

2.2 Platforms for Robotic Manipulation

In robotics, several researchers have designed and constructed arms with different features depending on the application to address. For example we can mention:

Milacron's arm, PUMA 560, WAN [101], DLR arm [41] and Cardea's arm [28]. The same applies to the design of hands where we can mention: the MIT/Utah's [50], the Stanford/JPL [89], the Barret's [102], DLR's [16] and the Shadow's [23] hand. There is also a wealth of work in the area of wrists. However, there are only a few platforms that have been constructed to research manipulation as a whole. Not surprisingly most of these platforms are humanoid robots. In this section, we will pay attention to these platforms.

- **Dexter** is a humanoid platform which has two Whole Arm Manipulators (WAM) [101], two Barrett hands [102], and a BiSight stereo head.

  The WAM arms have 7 direct-drive DOFs and cable transmission for force control. Each of the hands has 3 fingers and 4 DOFs. One DOF for each finger and one for rotating the fingers. The tips of each finger have an ATI load cell for force sensing. The BiSight stereo head can pan, tilt, and independently verge each camera. The cameras have control of focus, iris, and zoom. The head also has a binaural acoustic sensor consisting of four microphones. A VME architecture is used for computation.

  The work implemented in this platform [54, 56] shows an extensive use of force sensing in the fingers to deal with objects of unknown geometry. The speed of operation is limited, in part because of the lack of compliance in the fingers.

- **Robonaut** is a humanoid robotic platform designed to operate in space. It consists of a 2 DOF head (pan/tilt) and stereo cameras, two 7 DOF arms with force/torque cells at each shoulder (16 embedded sensors at each DOF), and two 14 DOF hands [70] whose design is based on the MIT-UTAH hand. The tactile sensing is still in development (miniature force cells for the fingertips) but currently uses FSRs and QTC resistors. This robot was designed to manipulate the same kinds of tools that humans do in space, controlled by teleoperators. However, due to the time-delays in communication the platform is becoming more autonomous.

Autonomous and semi-autonomous manipulation uses force-sensing from a few force cells in the shoulder and wrist. The arms are designed for high stiffness and consequently the harmonic geardrives are prone to damage. To solve this, the robot is covered with padding. Therefore, this platform is not fully designed to conduct exploration with its limbs.

- **Cog** is a humanoid robot designed to study embodied intelligence and social interaction. Cog has twenty-two mechanical DOFs: two 6 DOF arms, a 3 DOF torso, a 4 DOF neck, and 3-DOF combined in its eyes. The actuators in the arm are series elastic actuators [111]. Its design allows the robot interact safely with its environment and with people. These capability have been exploited in [112], [113] and [31].

- **Babybot** is composed of a head, an arm and an anthropomorphic hand. This robot was built to study sensory motor development and manipulation [81].

- **Domo** is a humanoid robot designed to study general dexterous manipulation, visual perception, and learning [27]. It has two arms and hands and a head. Its limbs use series elastic actuators [111].

- **Saika** is a humanoid robot [62] that consists of a two-DOF neck, dual five-DOF upper arms, a torso and a head. The hands and forearms used were designed according to the tasks to perform. The control used was behavior-based. Some of the goals of the robot were: hitting a bouncing ball, grasping unknown objects and catching a ball [63].

2.2.1 Robot Hardware Architecture

The robot OBRERO is shown in figure 2-1 where we can observe the hand, arm(originally created for the robot Domo [27]) and head. OBRERO's overall hardware architecture is presented in figure 2-2. In this figure we can observe that the hand and head controllers connect to different linux boxes using RS232 and that the arm controller uses CAN. The details about the hand, arm and head controllers are explained in

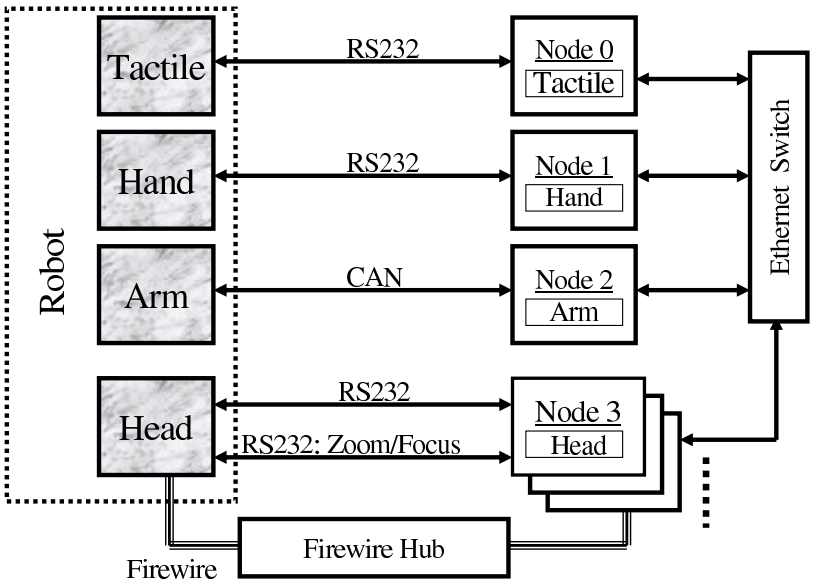


Figure 2-2: Overall architecture of OBRERO. The motor controllers of the Hand, Arm and Head are connected to different linux nodes via a serial RS232 or CAN. The boxes inside nodes 0,1,2,and 3 represent processes that handle the communication between a linux node and a motor controller or the tactile hardware. A network of microcontrollers reads the data from the tactile sensors and send the data to a linux node via RS232. The head is also connected to all the computers using a firewire network for acquiring images/sound and via RS232 to control zoom and focus.

sections 2.2.3, 2.2.4 and 2.2.5, respectively. The linux computers are interconnected by an 100 Mbps ethernet network. One of these nodes connects to the head via RS232 to control the zoom and focus of the camera. The camera is also networked with all of the computers by a firewire network to acquire images and sound. The details about these connections are described in section 2.2.5.

In this architecture, the information from each of the low level motor controllers (hand, arm, head) and from the tactile sensors is collected by linux nodes and made available to any software module. This feature gives flexibility for the software implementation because a program can run in any node independent of the feedback information needed.

2.2.2 Small and compliant actuator

In order to have a compliant hand, we need to have compliant actuators in its joints. An actuator that complies with this requirement is a series elastic actuator (SEA)

[88,111], however, it presents problems (described later) when they are to be used in small mechanisms. Consequently we started by designing an actuator that fits our specifications.

We start by defining SEA. SEAs are comprised of an elastic element, i.e., a spring, in series with a motor (see figure 2-3). By measuring the deflection of the spring, one can determine the force being applied by the system. Given that the spring is the only connective element between the actuator and the output, SEAs effectively reduce the mechanical impedance of the system. This can be better explained with an example: Imagine a robotic link actuated by an SEA. Any external force applied to the link will only be resisted by the flexible spring as opposed to the high inertia projected by the gearhead reduction. Therefore, the mechanical impedance of the whole system is defined by that of the spring.

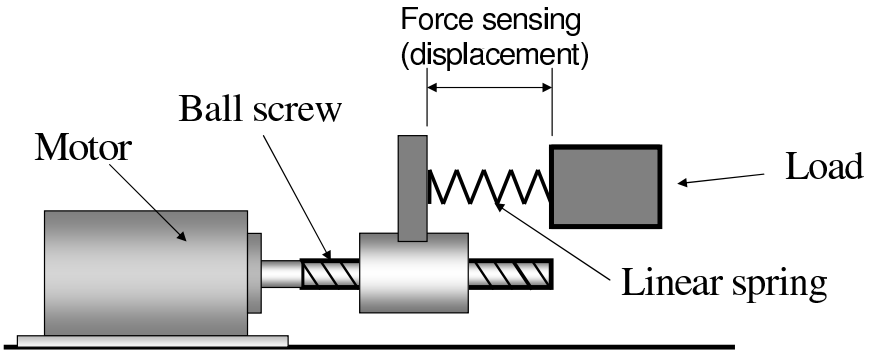


Figure 2-3: Conceptual depiction of an SEA, comprising a spring in series with a motor.

Although the spring also affects the reaction speed, or bandwidth, of the system, speeds still fall within an appropriate operational range for control applications. As a physical shock absorber, the spring also makes the robotic system less susceptible to and inherently reactive to unexpected impacts.

Traditionally there are both linear and rotary SEAs. The linear version requires precision ball screws to control the spring deflection. Although allowing for good mechanical transmission reduction, this constraint makes the system expensive and puts a limit on how small it can be. Conventional rotary SEAs require custom-made torsional springs, which are hard to fabricate and very stiff. This stiffness

practically obviates the benefits of an elastic element. Furthermore, the torsional spring deflection is generally measured by strain-gauge sensors that are cumbersome to mount and maintain. Both of these linear and rotary SEAs present joint integration problems.

Therefore, we designed and built a different actuator that is compact, easily-mountable and cheaper to fabricate while maintaining the features of SEAs [98].

Design

Figure 2-4 is a CAD rendering of the actuator. As will be explained, the module is comprised of: an actuated part, a transmission mechanism, and a mobile part. The actuated part is connected directly to the motor apparatus, while the mobile part is integrated into the moving output. The transmission mechanism transmits the motion from the actuated to the mobile part.

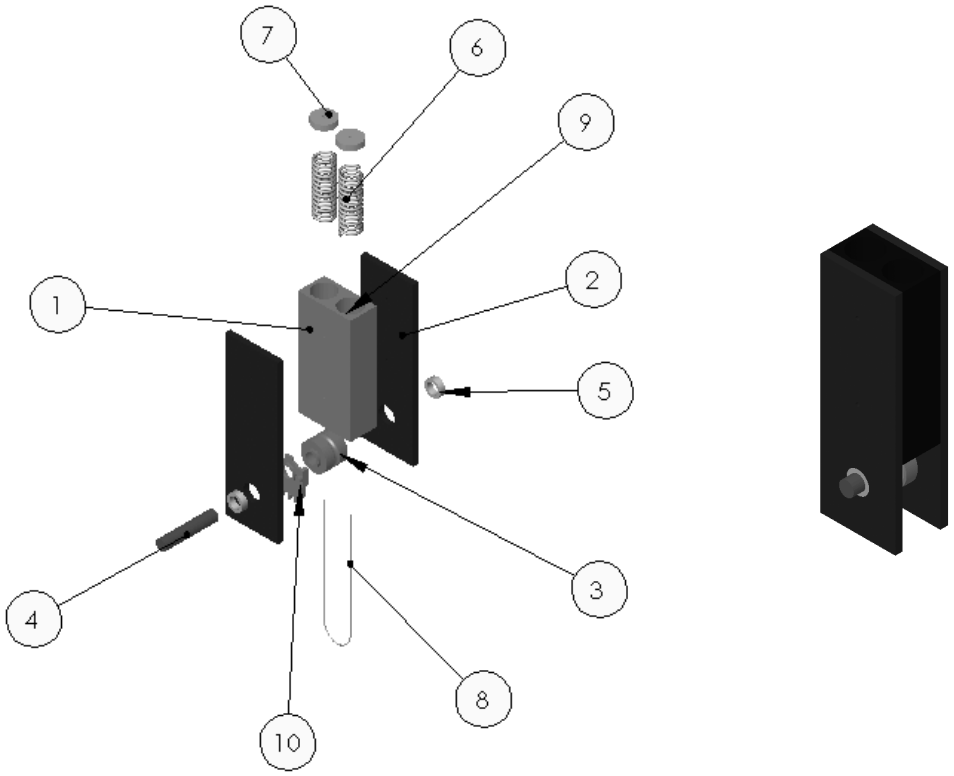


Figure 2-4: The force control actuator as a whole and an exploded, annotated view.1.Springbox 2.Plate 3.Wheel 4.Shaft 5.Bearing 6.Spring 7.Lid 8.Cable 9.Sping housing 10.Potentiometer

Description of the module functionality is easiest when we first consider the relationship between these subparts. The mobile part is composed of a spring box (1) sandwiched between two side plates (2). The actuated part consists of a wheel (3) fixed to a shaft (4) (which may be the motor shaft) and a potentiometer (10). The shaft/wheel assembly is mounted on bearings (5) in the two side plates. Therefore, the mobile part and the actuated part can rotate freely with respect to one another-at this point in the discussion, they are connected only by bearings. In other words, if a motor rotates the shaft, the wheel will move but the mobile part will not. The function of the potentiometer will be described below.

The transmission mechanism consists of two compression springs (6), two lids (7), and a cable (8). Each spring sits within a cylindrical, close-fitting shaft (9) in the spring box. An opening at one end of the shaft allows for spring and lid insertion.

The other end of the shaft has a flat bottom (against which the spring compresses) with a hole for the cable to pass through (see figure 2-5). Starting from its termination on one of the lids, the cable then runs through the center of one spring, out of the spring box, around the wheel and similarly back up through the other spring to terminate on its lid. The cable is fixed on the wheel to prevent it from slipping. Therefore, the springs can be effectively compressed between the bottom of their shafts and their respective lids through the tension in the transmission cable. Furthermore, both of the springs are initially compressed half way (described below). Due to this arrangement, any compression in one spring is reflected as an extension in the other. Because of this pre-compression of the springs, the routing of the cable during assembly may seem complicated; however, we present an elegant solution to this fabrication problem in Section 2.2.2.

In order to describe how the actuator works, we refer to the diagrams in figure 2-6. In the first diagram, we have a depiction of the wheel (of radius R) mounted on an axle and the cable. The cable is fixed to the wheel at Point A. The torque of the motor T_m is applied directly to the wheel's axle such that

$$T_m = R(F_1 - F_2) \tag{2.1}$$

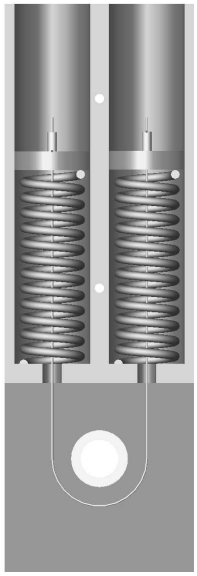


Figure 2-5: A cut-away view of the springbox showing the embedded springs (in their initial equally pre-compressed state) with their shafts and lids. As you can see, the cable terminates above each lid, runs down through the axis of each spring, and proceeds out the holes in the bottom of the shafts.

where F_1 and F_2 are the forces transmitted to the cable by the wheel .

The second diagram includes the springs. Each spring has rest length L and spring constant k, is capable of maximum compression C, and is initially pre-compressed to

$$L - x_i = C/2 \tag{2.2}$$

where x_i is the pre-compressed resting height of the springs. In order to keep the response of the actuator linear, its range must be maximally constrained to $\pi/2$ radians on either side of Point A. Pre-compressing the springs to $C/2$ ensures that the springs will not escape their shafts over the operational forces of the module. In other words,

$$C/2 = \phi_{max} R | 0 < \phi_{max} \leq \pi/2. \tag{2.3}$$

When the module (i.e., the mobile component) encounters a force such that it is held rigidly in place, we get a displacement of the springs (as shown in figure 2-7). That is, one of the springs is compressed a distance x and the other is extended by the same amount. Because the force on each spring is given by $F = k(x_i + x)$ and

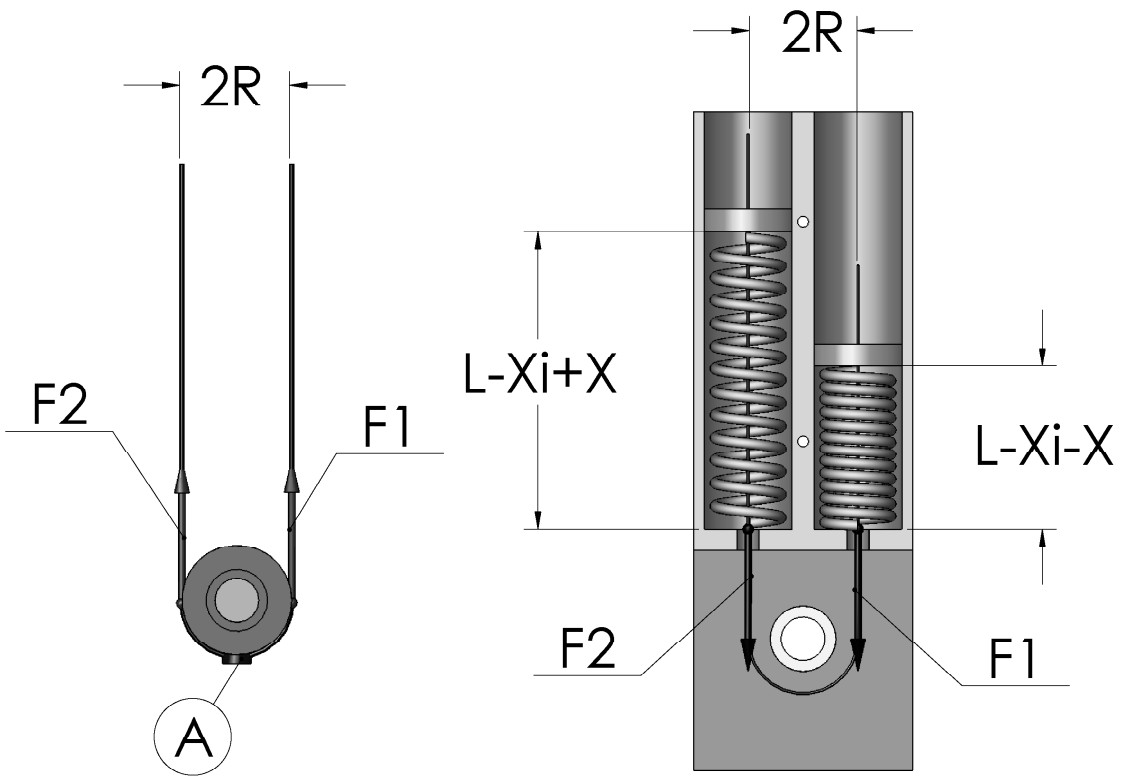


Figure 2-6: Free body diagrams of the actuator.

because this linear displacement is directly related to the rotation of the wheel by $x = \phi R$ (see figure 2-7), we end up with an output torque T_o:

$$T_o = 2k\phi R^2. \tag{2.4}$$

The potentiometer measures the relative displacement between the wheel (essentially the motor shaft) and the mobile part (essentially the moving link) to give us ϕ. Thus the actuator provides an effective measurement of the applied torques by measuring linear displacement of springs.

In order to control the torque applied by the actuator, a proportional controller is used. The controller acts on the position of the wheel with respect to the mobile part. This position control is enough to control the torque because of equation 4.

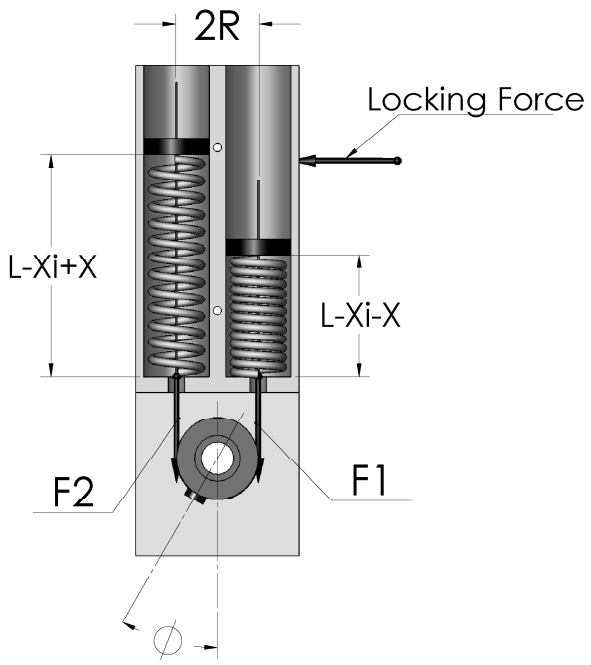


Figure 2-7: Actuator configuration with applied force holding it in place.

Mounting

One particularly important aspect of this module is its fabrication process. The whole actuator was designed to enable the pre-compression of the springs. Figure 2-8 depicts the assembly process which we describe in steps:

1. The wheel is fixed to the shaft which is mounted into one of the side plate bearings.

2. The springs are inserted into their shafts in the spring box and covered with their lids. The spring box is then temporarily placed tangent to the wheel (a distance of C/2 from its operational position).

3. A cable is threaded through the hole in one of the spring lids, down through the center of that spring, out of the spring box, around the wheel and similarly up the other side. The cable is then fixed to the wheel directly across from the spring box to keep it from slipping.

4. Next, cable terminators are crimped to the ends of the cable, flush with the outside of each lid. This is the configuration depicted in figure 2-8.

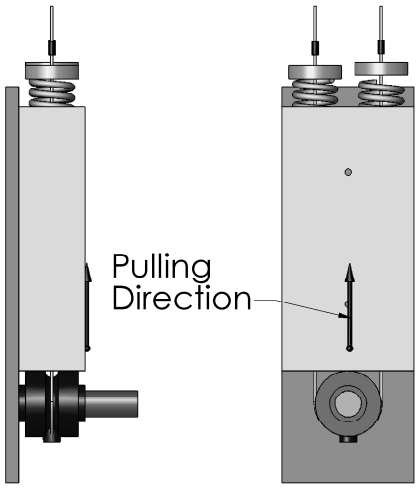


Figure 2-8: Mounting of the actuator.

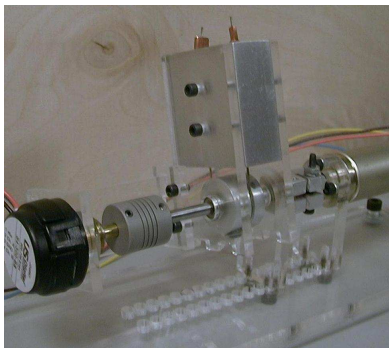


Figure 2-9: A testing prototype of the actuator made of acrylic and aluminum. The motor is off to the right.

5. Pulling the spring box away from the wheel effectively compresses the springs. The distance between the wheel and the operational position of the spring box was intentionally designed to be half the total compression of the springs. Thus by then fixing the spring box to the side plates, in its operational position, we have equally compressed both springs half way (see figure 2-5).

6. The modified potentiometer (or an encoder) is then attached to the wheel and the other side plate, which is finally mounted to the assembly.

Characterization

The prototype depicted in figure 2-9 was used to evaluate the linearity and the time-response of the actuator.

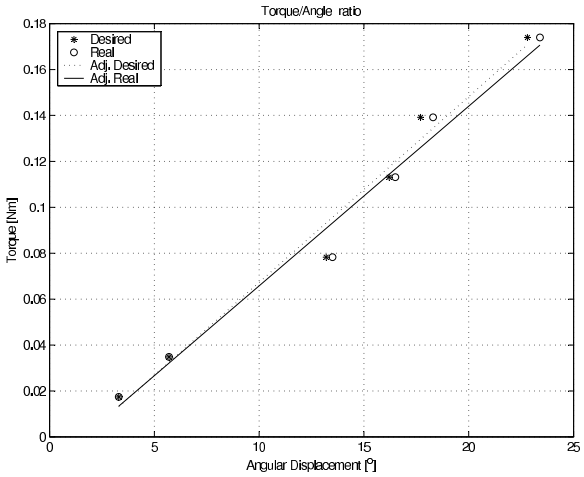


Figure 2-10: The figure shows the linear relation between the torque applied and the angular displacement in the actuator. We can also observe that the controller produces a torque close in value to the desired torque.

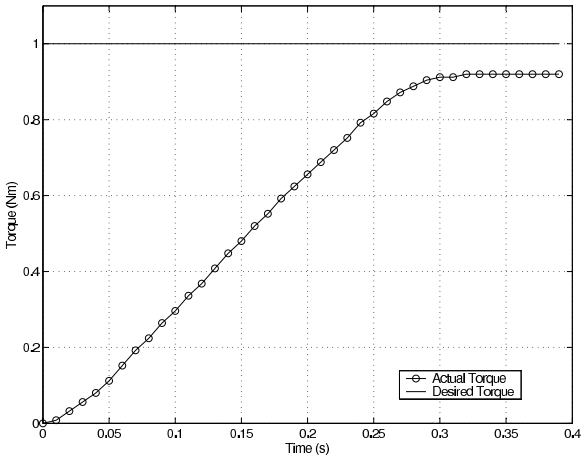


Figure 2-11: Time-response. We can observe that the actuator takes some time to deliver a desired torque.

The linearity of the actuator was determined by measuring the actual torque applied to the load and recording both the desired and actual displacement angles. The ratio between the torque and the angle yields the spring-constant of the actuator. The results of this test, shown in figure 2-10, demonstrate that the ratio between the actual displacement and the applied torque is fairly linear and confirm the expectations of the design. The actuator constant determined was 0.008 Nm/degree.

In order to determine the time-response of the actuator, we lock the mobile part and then apply a step function to the input of the actuator. The step function is applied by sending a desired force to the actuator at time zero. The controller of the actuator will move the motor until the desired angle is achieved. Given the current conditions, the motor will deform the springs and by measuring the displacement of the shaft with respect to the mobile part of the actuator, we determine the applied torque. In figure 2-11 we can observe the time it takes for the actuator to apply the desired torque to the load. We also observe that the damping of the system introduced by the springs is quite considerable. The rise time, defined as the time it takes the actuator to go from the 10% to 90% of the desired output, is around 270 ms.

2.2.3 Hand Design

General Description

In designing the hand we considered the following features important:

- Flexible configuration of the fingers
- Force sensing and mechanical compliance
- High resolution tactile sensing

As we describe the parts of the design, we will discuss the implementation of these features.

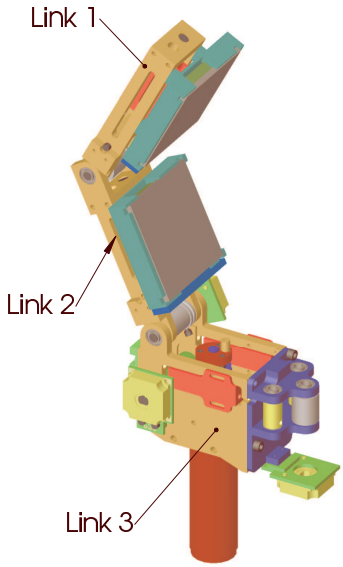


Figure 2-12: CAD rendition of a finger. It is comprised of three links. Link 1 and 2 have tactile sensors and their movement is coupled. Each of the three links is actuated using SEAs.

Finger Design

We start with the description of a finger. The size of each phalange of the fingers was imposed by the size of the tactile sensors originally considered. Each finger consists of three links as depicted in figure 2-12. Links 1 and 2 are coupled with a ratio of 3/4. The axes of these two links have an actuator, which is described in section 2.2.2. This actuator has several functions: reading the torque applied to the axes, reducing the mechanical impedance of each link, and allowing the two links to decouple their movement.

The first two functions are common features of this kind of actuator and the last one is a consequence of the actuator construction.

This decoupling is useful to do grasping as described in [102]. For instance, we can observe in figure 2-13 that when link 2 contacts an object, link 1 can still keep moving to reach the object, while link 2 continues to apply force on the object.

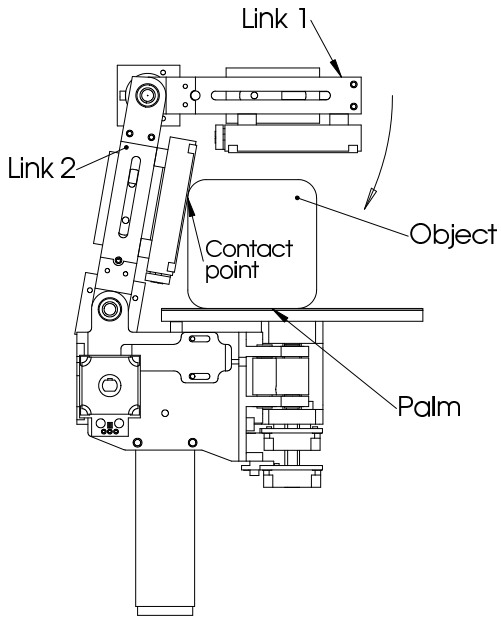


Figure 2-13: Link 2 has made contact with an object and stopped moving but keeps pressing against the object. Link 1 continues moving.

In order to move links 2 and 1, there is a motor located on link 3. The torque is transmitted using a cable from the motor to the two actuators on their respective links (see figure 2-14). Cable is used as a transmission mechanism because unlike gears it does not have backlash problems. The different diameters of the wheels of the actuators determine the transmission ratio.

An important consideration when we are working with cables is the tension mechanism. The size of the tension mechanism in this case had to be small so that it could fit inside link 3. The mechanism used is described in figure 2-14.

In this figure, we can also observe the presence of an idler wheel that helps to route the cable and has a potentiometer attached to its axis to determine the absolute position of the links when they are coupled. When they are decoupled we need to consider the information available in the actuators to get the absolute position.

Tactile sensors are mounted in links 2 and 1. The details of these sensors are described in section 2.2.3. The sensor used are sensitive to small forces in any direction,

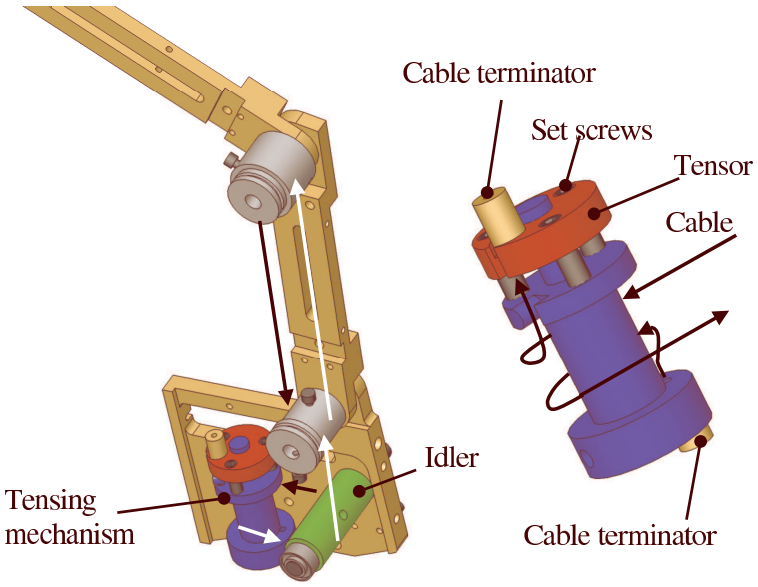


Figure 2-14: On the left we can observe the cable routing in a finger. The cable comes from the tensing mechanism, goes under the idler wheel and continues to the wheels on each axis. On each of these wheels the cable is wrapped around and clamped using the screws shown on the wheels. The cable wrapped on the top wheel goes down, wraps around the lower and the idler wheels and ends on the tensing mechanism. A detail of the tensing mechanism is shown on the right of the figure. It consist of a wheel that goes connected to the motor and a lid that slides on a shaft. The cable with a terminator comes from the bottom of the wheel, continues its trajectory as described before and ends with another terminator on the lid. The lid tenses the cable by increasing the distance between itself and the wheel using the setscrews. The setscrews fit in holes that avoid rotation of the lid.

conform to the objects that is being touched and increase the friction between the object and the hand.

An extra feature of the finger, derived from the actuator, is the possibility of bending to push objects, as described in figure 2-15. This feature is a consequence of the low mechanical impedance of the actuator and is very important when the hand comes in contact with an object. This deflection allows OBRERO to detect the collision, conform the finger to the object, and minimize the chances of damage.

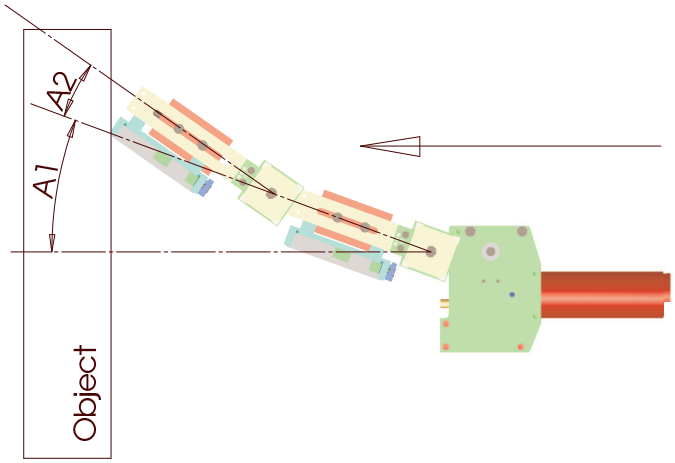


Figure 2-15: When a finger pushes against an object, it passively bends and does not break thanks to the mechanical compliance of the actuators.

Palm and Three Fingers Design

The hand is comprised of three fingers, each like the one described above, arranged around a palm as shown in figure 2-16. In this configuration, finger 2 is fixed with respect to the palm but fingers 1 and 3 can move in the direction shown by the arrows. Fingers 1 and 2 can be opposed to each other as a thumb and index finger in a human hand. Fingers 1 and 3 can also be opposed as shown in figure 2-17. The degree of freedom of the fingers 1 and 3 around the palm allow the hand to arrange the fingers to obtain an adequate configuration for grabbing objects with a variety of shapes.

The rotation of fingers 1 and 3, respect to the palm, is driven by a variation of the

actuator described in section 2.2.2. This provides these fingers with the advantages described earlier. The torque for each axis is provided by a DC motor which transmits movement through a cable mechanism. However, the cable tensing mechanism is simpler than the one on the fingers because it does not have to move coupled links. Therefore, the tensing mechanism of the actuator is enough. This mechanism is shown in figure 2-18.

The palm has the same kind of tactile sensor as the one on the fingers and is described in section 2.2.3).

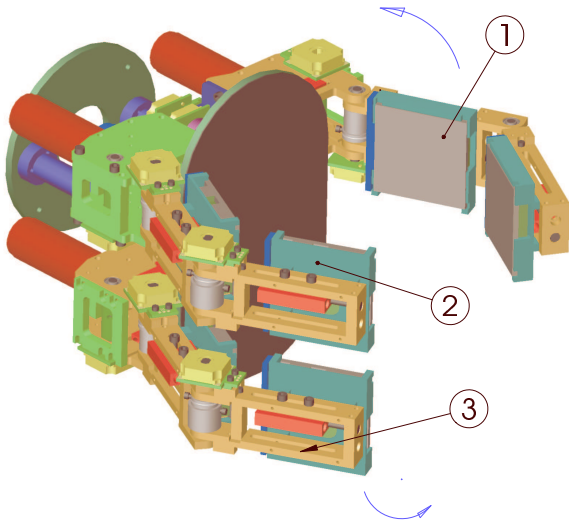
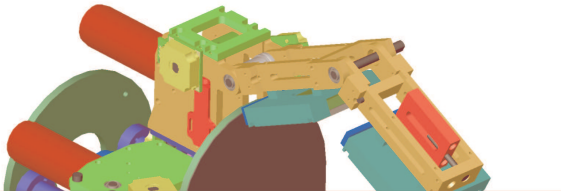


Figure 2-16: The arrangement of the fingers around the palm. Finger 2 is fixed to the palm while fingers 1 and 3 move up to 90° in the directions indicated by the arrows.

Tactile Sensor

In the original design we considered tactile sensors with high spatial resolution. The best option was using a mouse pad composed of force sensing resistors (FSR). A touch pad from Interlink Electronics provides an array of FSRs whose density is 200 dots/inch and 7 bits magnitude of the force/pressure applied. These sensors report