Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space: i-SAIRAS 2001, Canadian Space Agency, St-Hubert, Quebec, Canada, June 18-22, 2001.

Underactuation in Space Robotic Hands

Thierry Laliberté and Clément M. Gosselin

Département de Génie Mécanique, Université Laval, Québec, Québec, Canada, G1K 7P4
thierry@gmc.ulaval.ca gosselin@gmc.ulaval.ca

Keywords Grasping, robotics, hand, gripper, underactuation, flexible, selfadaptive, reconfigurable, space.

Abstract

This paper presents the development of a selfadaptive and reconfigurable robotic hand for space applications which is versatile, robust and easy to control. This hand has three fingers and each of the fingers has three phalanges. It will be shown that the selfadaptability of the hand is obtained using underactuation within and among the fingers of the robotic hand. Indeed, underactuation between the phalanges of a finger is realized using linkages and springs while the underactuation among the fingers is implemented by a special one-input/three-output differential. An additional degree of freedom (dof) is used to rotate two of the fingers in order to reconfigure the hand and fit the general geometry of the object to be grasped. Overall, the hand has ten dofs, actuated by two motors, i.e., one for opening/closing of the fingers and one for orienting the fingers. In a specific application, the robotic hand is a passive tool and the actuation is provided by the socket torque of an ORU Tool Change Out Mechanism (OTCM).

1 Introduction

Complex tasks involving the grasping of various objects in an unstructured environment are still being performed by human operators, even in hostile environments. One of the main obstacles to the teleoperation or automation of these tasks has been the lack of versatile grasping tools, i.e., of robotic hands. In space applications and in many other applications, the manipulation of objects with very complex mechanical hands [1] [2] or human hands is often not essential and grasping devices are sufficient. However, simple grippers [3] are not appropriate in most cases because they are not capable of adapting to the shape of different objects. Hence, the development of versatile robotic hands which are capable of grasping a wide variety of objects with a very simple control structure is of great interest for many applications, including the use of robotic devices in space. These hands are obtained with the help of underactuation.

2 Selfadaptation from underactuation

An underactuated mechanism is one which has fewer actuators than degrees of freedom (dofs). When applied to mechanical fingers, the concept of underactuation leads to selfadaptability. Selfadaptive fingers will envelope the objects to be grasped and automatically adapt to their shape with only one actuator and without complex control strategies. In order to obtain a statically determined system, elastic elements and mechanical limits must be introduced in underactuated mechanisms. While a finger is closing on an object, the configuration of the finger at any time is determined by the external constraints associated with the object. When the object is fully grasped, the force applied at the actuator is distributed among the phalanges.

A closing sequence of an underactuated two-dof finger is shown in Figure 1 in order to clearly illustrate the concept of underactuation. The finger is actuated through the lower link, as shown by the arrow in the figure. Since there are two dofs and one actuator, one (two minus one) elastic element must be used. In the present example, an extension spring is used which tends to maintain the finger fully extended. A mechanical limit is used to keep the phalanges aligned under the action of this spring when no external forces are applied on the phalanges. It should be noted that the sequence occurs with a continuous motion of the actuator. In *a)*, the finger is in its initial configuration and no external forces are present. The finger behaves as a single rigid body in rotation about a fixed pivot. In *b)*, the proximal phalanx makes contact with the object. In *c)*, the second phalanx is moving with respect to the first one and the finger is closing on the object since the proximal phalanx is constrained by the object. During this phase, the actuator has to produce the force which is required to extend the spring. Finally, in *d)*, both phalanges are in contact with the object and the finger has completed the shape adaptation phase. The forces applied at the actuator are distributed among the phalanges.

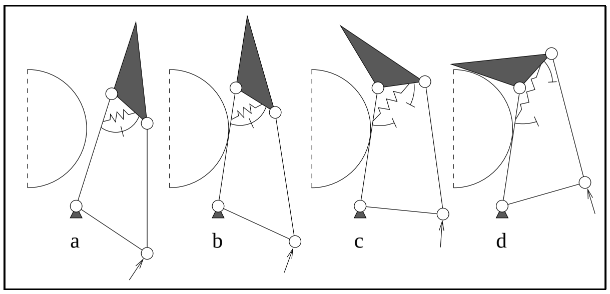


Figure 1: Closing sequence of an underactuated two-dof finger.

A few underactuated fingers have been proposed in the literature. Some of them are based on linkages while others are based on tendon-actuated mechanisms. Examples of underactuated hands based on tendons are given in [4], [5] and [6]. Tendon systems are generally limited to rather small grasping forces and they lead to friction and elasticity. Hence, for applications in which large grasping forces are expected, linkage mechanisms are usually preferred and the present work is limited to the study of the latter mechanisms. One of the only studies on the statics of underactuated grippers is presented in [7]. In the latter reference, the static analysis of a system composed of two fingers, each having two dofs, is performed and some results are given to present the advantages of underactuated fingers over a simple parallel gripper. In [8], an underactuated hand with three fingers is presented. Each of the fingers is based on a two-dof mechanism having two phalanges and one actuator. Additionally, a special mechanism is introduced in order to allow the distal phalanges to be maintained orthogonal to the palm when precision grasps are performed. In [9], a mechanical hand resembling the human hand is presented. Each of the fingers is composed of three phalanges but has only two dofs since the motion of the last phalanx is directly coupled to the motion of the second phalanx. Another type of underactuation can also be found in the literature [10] [11]. It consists in using brakes or clutches in order to sequentially drive the different dofs with a single actuator. Such systems are different from the underactuated mechanisms described above in behaviour and implementation. Finally, it should be clearly understood that robotic or prosthetic hands in which the motion of the fingers is mechanically coupled [12] are not underactuated. Indeed, they are designed to mimic the motion of human fingers but the relative motion of the phalanges is determined at the design stage and therefore no shape adaptation is possible.

3 Three-dof underactuated finger

As presented in the literature review, the existing underactuated fingers based on linkages have two phalanges or three coupled phalanges with two dofs. However, it is desirable to design an underactuated finger with three phalanges and three dofs since it leads to more stable grasps and more efficient shape adaptation. The result is a behaviour similar to that of human fingers. This finger mechanism has been introduced in [13] and is illustrated in Figure 2. In order to obtain a three-dof finger with three phalanges, a four-bar mechanism is added to the five-bar mechanism of a two-dof finger. It is important

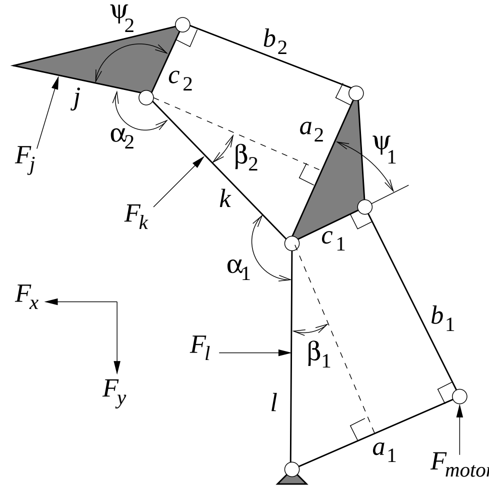


Figure 2: Three-dof shape adaptation mechanism in an average configuration.

to notice that the behaviour of the finger is determined by its geometry, dimensioned at the design stage, since the different dofs cannot be controlled independently. Hence, the choice of the design parameters is a crucial issue in order to obtain stable grasps and a proper distribution of the forces among the fingers.

The different parameters involved in the design, illustrated in Figure 2, are now discussed. The length of the phalanges, i.e., l, k, j are fixed from comparison with other existing fingers and experimentation with a finger model on objects to be grasped. The remaining design variables are a_i, b_i, c_i and ψ_i. In order to introduce design constraints and to reduce the number of independant variables, some relationships between these parameters are imposed, reducing the number of variables to two. In [14], it has been shown that the behaviour of the fingers is mainly dictated by the ratios $R_i = a_i/c_i$. In order to minimize the 'thickness' of the finger, the length c_i should be as small as possible but is limited by mechanical interference considerations. Therefore, c_i is fixed, and then a_i is fixed for a given ratio. The performance of the finger regarding the stability of behaviour, the mechanical interferences and the internal forces is correct if the transmission angle is close to 90 degrees when the finger is in an average configuration, as illustrated in Figure 2. The parameters b_i and ψ_i can be computed from this criterion. First, the average configuration of the finger is defined as the configuration in which angles α_1 and α_2 are given by

$$\alpha_i = \frac{\alpha_{i,min} + \alpha_{i,max}}{2}, \qquad i = 1, 2 \tag{1}$$

where $\alpha_{i,min}$ is the minimum value of angle α_i and $\alpha_{i,max}$ is its maximum value. Then, the average angles β_1 and β_2, as defined in Figure 2, are given by

$$\beta_1 = \arcsin\left(\frac{a_1 - c_1}{l}\right), \beta_2 = \arcsin\left(\frac{a_2 - c_2}{k}\right) \tag{2}$$

which leads to values of b_i given by

$$b_1 = l\cos\beta_1, \qquad b_2 = k\cos\beta_2 \tag{3}$$

and to the values of ψ_i given by

$$\psi_1 = \pi - \alpha_1 + \beta_2 - \beta_1, \qquad \psi_2 = \frac{3\pi}{2} - \alpha_2 - \beta_2 \tag{4}$$

Using the above equations as design constraints, the parameters can be computed as functions of the ratios R_1 and R_2.

A study is performed on fingers with different combinations of ratios R_i, giving an overview of possible fingers. To perform the study, a series of grasps are performed on circular objects of different sizes and at different positions, in order to simulate different sizes and shapes of objects, using a simulation tool presented in [14]. The main criteria used to estimate the performance of the fingers are:

a) The sum of the forces applied by each finger on the object must be directed towards the palm (F_y) and the opposite finger (F_x) in order to obtain a stable grasp. Also, the forces F_x should be larger than the forces F_y in order to obtain balanced grasps, since the forces F_y work in cooperation (towards the palm) and the forces F_x work in opposition (against each other). That is, $F_x = EF_y$, where the value of E depends on the type of grasp and is generally approximately equal to 2. The performance index associated with the resulting forces is given by the sum of the smallest force for each of the m objects grasped.

$$I_{xy} = \frac{\sum_{i=1}^{m} \min(F_{x,i}, EF_{y,i})}{m} \tag{5}$$

b) The forces should be well distributed among the phalanges in order to avoid large local forces on the object. The corresponding index is defined as the ratio of the total force on the three phalanges divided by the largest force.

$$I_{lkj} = \frac{\sum_{i=1}^{m} \frac{F_{l,i}+F_{k,i}+F_{j,i}}{\max(F_{l,i},F_{k,i},F_{j,i})}}{m} \tag{6}$$

c) An *equilibrium point* should exist on the last phalanx in all configurations in order to ensure feasible grasps. The equilibrium point is defined as *the point of contact on a phalanx which leads to static equilibrium, for a given configuration, when no contact occurs at the preceding phalanx (see [14] for details).* If the equilibrium point is not located on the last physical phalanx, then the grasp is not possible and the object will be ejected. If the equilibrium point is on the last physical phalanx, the index $I_{ep} = 1$; if it is not, the index $I_{ep} = 0$.

d) The finger mechanism should be as compact as possible. If the finger is sufficiently compact, the index $I_c = 1$. Otherwise, the index is between 0 and 1.

The performance indices are combined in order to obtain a global index $I_G = I_{xy}^2 I_{lkj} I_{ep} I_c$ for each of the fingers. The index I_{xy} is squared since it is a more important criterion. A graph of I_G as a function of R_1 and R_2 is presented in Figure 3. An effective finger can then be chosen among the best values of I_G. For example, $R_1 = 2$ and $R_2 = 2.5$.

3.1 Parallel precision grasp mechanism

Underactuated fingers cannot perform precision grasps while maintaining the distal phalanges parallel to each other, for objects of different sizes. However, this feature allows more stable grasps when only the tips of the fingers are used and is very often feasible with simple grippers. A mechanism has been proposed in order to achieve this behaviour for a two-dof underactuated finger [8]. A mechanism achieving a similar behaviour with the third phalanx of a

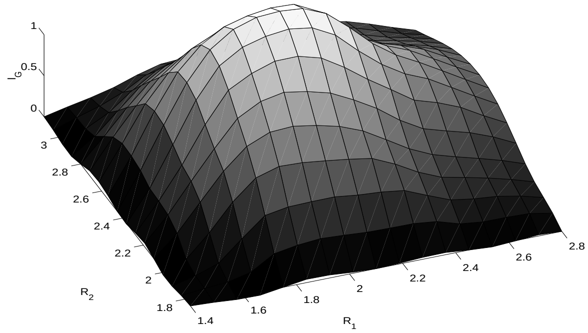
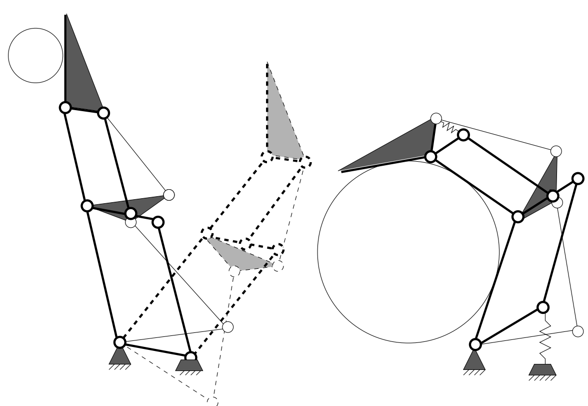


Figure 3: Global performance index.

three-dof underactuated finger has been developed here [13] and is shown in Figure 4. It is composed of two parallelograms mounted in series. This mechanism is coupled to the phalanges of the finger but not to the other links of the shape adaptation mechanism (it is moving on a parallel plane). Two mechanical limits with springs at the top and bottom ends of the mechanism allow precision grasps to be performed and the adaptation to power grasps if necessary. This is illustrated in Figure 4. In configurations (a), from dashed lines to full lines, a parallel motion of the distal phalanx is accomplished, by maintaining the parallelogram mechanism on its mechanical limits. In (b), a power grasp is performed, with contacts on all phalanges. In this case, the parallelogram mechanism is moved away from its mechanical limits and the distal phalanx is no longer maintained parallel.



(a) (b)

Figure 4: The parallel precision grasp mechanism (dark lines). (a) parallel precision grasps. (b) power grasp.

4 Underactuation among fingers

In addition to underactuation in fingers, it is possible to include underactuation among fingers. The principle of underactuation among fingers has been used in the literature for the actuation of a few coupled-motion fingers [15] [16], each mechanism adding one degree of underactuation. In the present hand, a one-input/three-output differential is used, adding two degrees of underactuation. Therefore, if some fingers are blocked, the remaining fingers will continue to close until they properly grasp the object. The force is fully applied only when all the fingers have properly made contact with the object. The system is illustrated in figure 5. The differential is

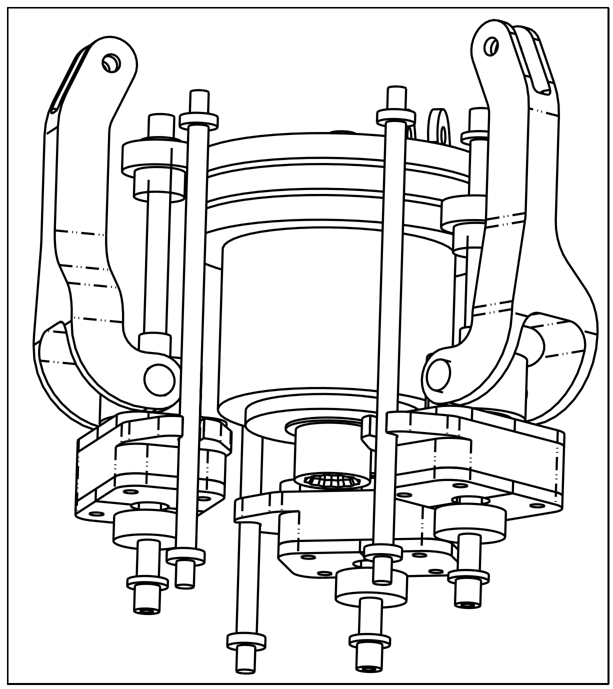


Figure 5: One-input/three-output differential and transmission screws.

composed of two planetary gear trains. The first planetary gear train has the carrier as input and the sun gear and internal gear as outputs. The second planetary gear train has the internal gear of the first planetary gear train as input and the sun gear and internal gear as outputs. Therefore, the three general outputs are the sun gear of the first planetary gear train, the sun gear of the second planetary gear train and the internal gear of the second planetary gear train. In order to obtain proper distribution of the power, the three outputs should have the same or close to the same output torque. This torque distribution is obtained by a proper selection of the gear ratios. The three outputs of the differential are coupled to transmission screws through gears. These screws transform the rotational movement in translational movement and allow selflocking of each of the fingers for proper stability. The force is transmitted to the fingers through an actuation bar. To synchronize the closing of the fingers, the fingers are opened until they all reach their maximum opening limit. When no external force is exerted on the fingers, the outputs of the differential stay synchronized with the help of internal friction.

5 Reconfiguration

In order to adapt to the general geometry of the object to be grasped, the hand can be reconfigured by modifying the orientation of the fingers. Note that this feature is widely used in the literature, in several different versions. In the proposed hand, two of the fingers can be oriented. The orientation of the two fingers is coupled by a geared mechanism, shown in figure 6. The fingers are placed on the vertices of an equilateral triangle. The required grasping orientations of the fingers can be reduced to three main grasping configurations : cylindrical, spherical and planar, as illustrated in figure 7. In the cylindrical configuration, two fingers point in the same direction while the third one points in the opposite direction and moves between the other two. In the spherical configuration, the three fingers are oriented towards the center of the triangle. In the planar configuration, two fingers are directly facing each other and the third finger is not used. In the planar configuration, where the third finger is not used, its closing is blocked at an output of the differential by a stopper activated by the orientation mechanism.

6 Robotic grasping hand

The combination of the preceding features leads to a robotic hand with ten dofs and two degrees of actuation, illustrated in figure 8. One actuator is used to drive the differential which drives the opening/closing of each of the three fingers via a transmission screw. The second actuator is used to drive the orientation of the fingers. To the knowledge of the authors, the hand includes the combination of the underactuation of the phalanges of a finger and the fingers of a hand for the first time.

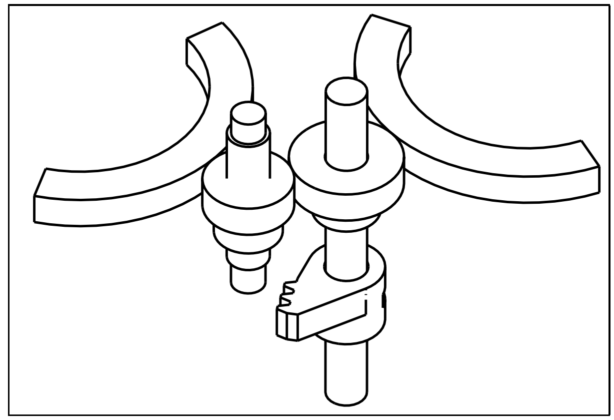


Figure 6: The orientation mechanism. The two sections of gear are attached to the two orientable fingers. When appropriate, the teeth of the stopper will engage with one of the outputs of the differential.

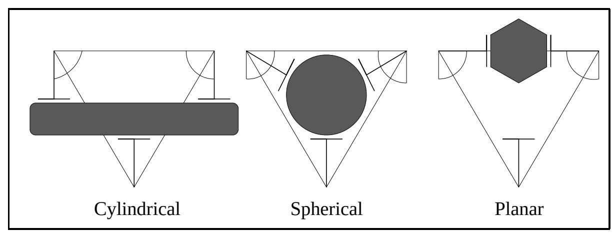


Figure 7: Main configurations of fingers.

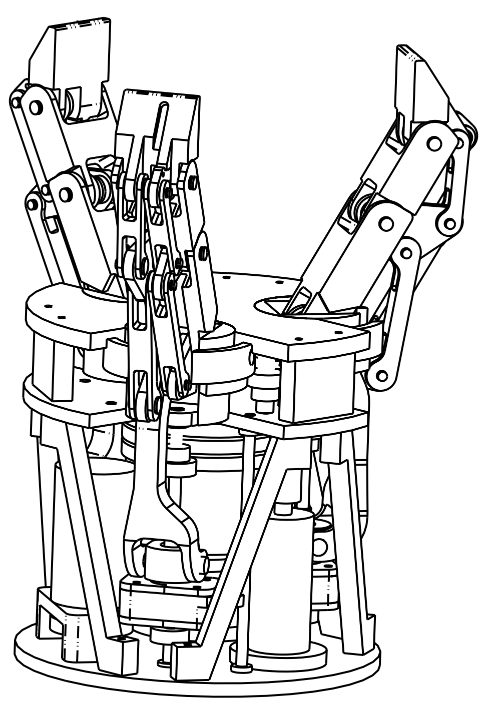


Figure 8: CAD model of the hand with motors.

7 ISS implementation

In a ISS (International Space Station) specific implementation, the hand, called SARAH (Self-Adapting Robotic Auxilary Hand) is driven and handled by an OTCM (ORU Tool Change Out Mechanism), the end effector placed at the end of the SPDM (Special Purpose Dextrous Manipulator) arms. Therefore, SARAH is considered as a tool. In this case, the power is provided by the socket torque and advance of the OTCM. The socket advance has only limited power and control possibilities, therefore the two tasks (open/close and orientation) must be actuated by the powerful and controlable socket torque.

7.1 Indexing mechanism

The switching of the power of the socket torque between the two tasks is performed by the socket advance with the help of an indexing mechanism, illustrated in figure 9. The power of the socket torque is transmitted to the sockets of the differential or orientation mechanism through the main shaft. It is free to rotate and translate in the hole of the bottom plate, and includes nuts at its ends. An indexing ring is free to rotate but fixed in translation on the main shaft. Indexing pins are attached to the micro interface and are inserted in the grooves of the indexing ring in order to guide the motion of the indexing ring. A compression spring is inserted on the main shaft, between the bottom plate and a shoulder on the main shaft, in order to keep the main shaft backwards. In this position, no mechanism sockets are engaged. When the OTCM socket pushes on the main shaft, it advances against the spring. This advance is stopped by the indexing pins up to a position that engages the main shaft on one of the two mechanism sockets, depending on the length of the groove engaged. Then, if the socket torque is activated, the corresponding mechanism is activated. Each time the socket of the OTCM is releasead and advanced, the power is switched between the two mechanism sockets.

7.2 Orientation

In order to obtain predefined self-locked configurations, the orientation of the fingers is driven via a Geneva mechanism. The input is provided via a socket on the Geneva driver. When the Geneva mechanism is in the moving phase, the pin of the Geneva driver is in one of the slots of the Geneva wheel. During this phase, the Geneva driver moves the Geneva wheel by 90 degrees. When the Geneva

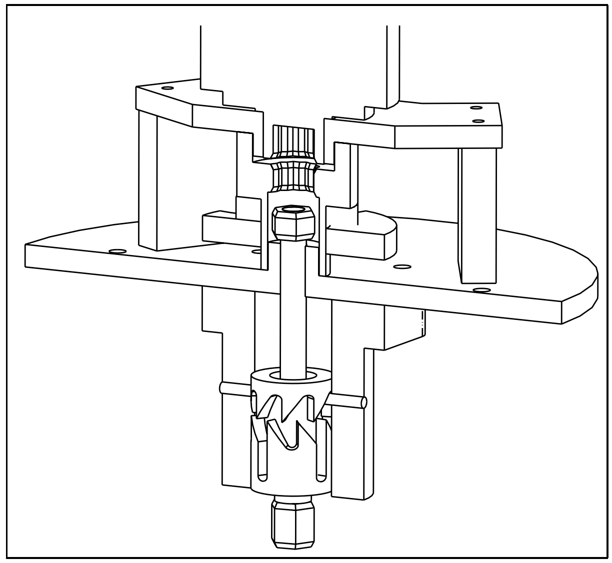


Figure 9: The indexing mechanism.

mechanism is in the dwell phase, the Geneva wheel is locked by the locking disk of the Geneva driver. Also, the Geneva driver is free to rotate, allowing play for easy insertion of the nut of the main shaft in the socket if they are not properly aligned. During this phase, the fingers are locked in their orientation even if they are not driven. To restrain the orientation of the fingers in the appropriate range, one of the four slots of the Geneva wheel is filled to stop the rotation of the Geneva mechanism.

8 Prototypes and experimentation

A plastic (P1) and a metal (M1) prototypes of SARAH have been built. The fingers are 5.5 inches long and placed on a circle of 3.75 inches diameter. SARAH P1 has been tested manually with a motorized screwdriver. Some grasps are illustrated in Figure 10. SARAH M1, illustrated in Figure 11, has been tested with the help of an apparatus developed to emulate the OTCM, named Laval OTCM (LOTCM). In order to measure the forces that are applied, a force/torque sensor is used. It is placed between half cylinders to emulate a cylindrical object of 3.5 inches of diameter.

The main results of the validation and characterization of SARAH M1 are summarized here. The grasping characteristics of SARAH M1 have been measured in four different configurations covering three different grasps, i.e., cylindrical power grasp (opposing fingers and palm-finger opposition), cylindrical precision grasp and planar precision grasp. The grasping force vs input torque relationship of SARAH M1 has been obtained experimentally for the previous grasps and is presented in Figure 12. The curves result from the application of linear regression on the measured data. The tests show that SARAH M1 is able to grasp more than 50 lbs in a cylindrical power grasp of a 3.5 inches cylinder. The force could be larger with a smaller cylinder. Also, the tests show that SARAH M1 is able to grasp more than 25 lbs in a cylindrical precision grasp and more than 15 lbs in a planar precision grasp. This is for a socket torque of 60 lb-in. The above results show the grasping force that can be applied on an object. However, since the fingers of SARAH are self-locking, the external forces that can be resisted by SARAH are higher than the motorized grasping forces. Indeed, external forces of more than 60 lbs were applied and SARAH M1 resisted properly.

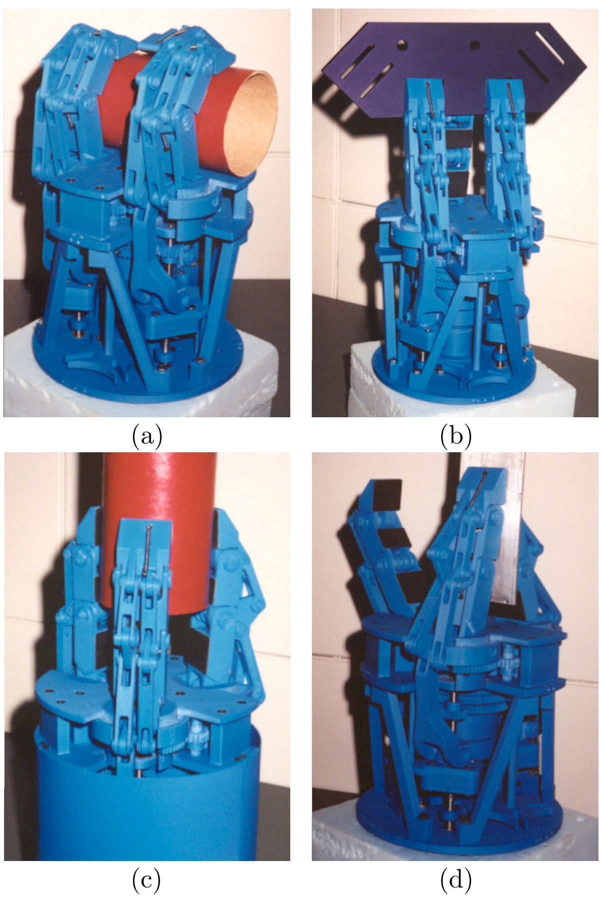


Figure 10: Examples of grasps with SARAH P1: (a) Cylindrical power grasp. (b) Cylindrical precision grasp. (c) Spherical precision grasp. (d) Planar precision grasp, note that one of the fingers is blocked open to allow an effective grasp.

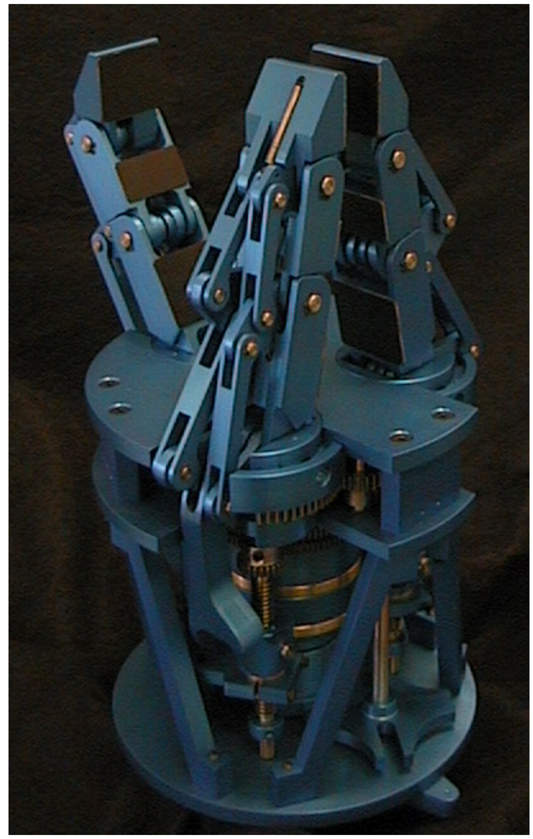


Figure 11: The SARAH prototype M1.

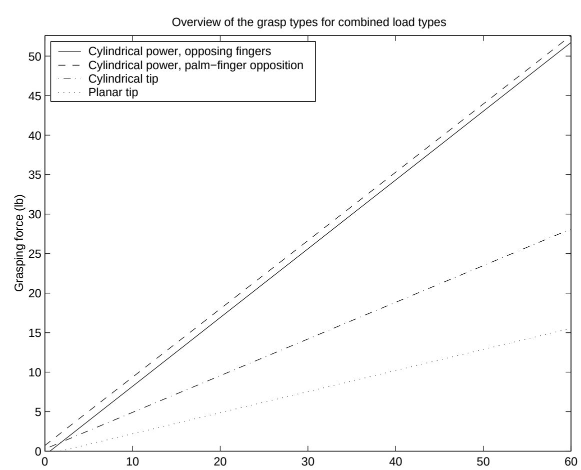


Figure 12: The grasping force vs input torque relationship of SARAH M1.

9 Conclusion

In this paper, it has been shown that the combination of underactuation into and among fingers can be used to design a ten-dof hand driven by only two motors. This selfadaptive and reconfigurable hand is covered by a pending patent. The robotic hand developed in this project is especially useful where various sizes and shapes of objects are to be grasped, and where simplicity of use and control is important. In this sense, SARAH is especially well suited for the context of the ISS. Additionally, its interface is already compatible with the OTCM of the SPDM arms. Although it has great grasping flexibility, SARAH is not able to perform manipulation. Therefore, SARAH is intended to help the astronauts and not to replace them. Experimentation has demonstrated the capability of a prototype to grasp various shapes and sizes of objects with sufficient force and appropriate stability. Current work includes the development of other versions of the hand for industrial use or other space applications, as well as the development and control of a hand equiped with tactile sensors.

Acknowledgements The work reported here has been performed under a research grant from NSERC and MDRobotics.

References

[1] S.C. Jacobsen, J.E. Wood, D.F. Knutti, and K.B. Biggers, "The UTAH/M.I.T. Dextrous Hand: Work in Progress", *The International Journal of Robotics Research*, Vol. 3, No. 4, pp. 21–50, 1984.

[2] M.T. Mason, J.K. Salisbury, *Robot Hands and the Mechanics of Manipulation*, The MIT Press, Cambridge, 1985.

[3] F.Y. Chen, "Gripping Mechanisms for Industrial Robots: An Overview", *Mechanism and Machine Theory*, Vol. 17, No. 5, pp. 299–311, 1982.

[4] J.D. Crisman, C. Kanojia and I. Zeid, "Graspar : A Flexible, Easily Controllable Robotic Hand", *IEEE Robotics and Automation Magazine*, pp. 32–38, June 1996.

[5] D.F. Graham, "Artificial Hand and Digit Therefor", US Patent 5200679, 1993.

[6] S. Hirose and Y. Umetani, "The Development of Soft Gripper for the Versatile Robot Hand", *Mechanism and Machine Theory*, Vol. 13, pp. 351–359, 1978.

[7] H. Shimojima, K. Yamamoto and K. Kawawita, "A Study of Grippers with Multiple Degrees of Mobility", *JSME International Journal*, Vol. 30, No. 261, pp. 515–522, 1987.

[8] S.J. Bartholet, "Reconfigurable End Effector", US Patent 5108140, 1992.

[9] R.M. Crowder and D.R. Whatley, "Robotic Gripping Device Having Linkage Actuated Finger Sections", US Patent 4834443, 1989.

[10] N. Ulrich and V. Kumar, "Grasping Using Fingers with Coupled Joints", *Proceedings of the ASME Mechanisms Conference*, Vol. 15-3, pp. 201–207, 1988.

[11] S. Lee, "Artificial Dexterous Hand", US Patent 4946380, 1990.

[12] J. Zhang, G. Guo and W.A. Gruver, "Optimal Design of a Six-Bar Linkage for an Anthropomorphic Three-Jointed Finger Mechanism", *Proceedings of the ASME Mechanisms Conference*, Phoenix, vol. DE-45, pp. 299–304, 1992.

[13] C.M. Gosselin and T. Laliberté,"Underactuated Mechanical Finger with Return Actuation", US patent 5 762 390, 1998.

[14] T. Laliberté and C.M. Gosselin, "Simulation and Design of Underactuated Mechanical Hands", *Mechanism and Machine Theory*, Vol. 33, No. 1/2, pp. 39–57, 1998.

[15] M. Rakik, "Multifingered Robot Hand with Selfadaptability", *Robotics and Computer-Integrated Manufacturing*, Vol. 5, No. 2-3, pp. 269–276, 1989.

[16] G. Guo, X. Qian and W.A. Gruver, "A Single-DOF Multi-Function Prosthetic Hand Mechanism With an Automatically Variable Speed Transmission", *Proceedings of the ASME Mechanisms Conference*, Phoenix, vol. DE-45, pp. 149–154, 1992.