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A Joint-Selective Robotic Gripper with Actuation Mode Switching

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***Abstract*— Robotic grippers in research and industry make constant trade-offs between payload capacity, dexterity, cost and performance. We try to address all these problems together by developing a dual mode gripper that can switch between a fully actuated precision mode and a grasping mode. In the underactuated grasping mode, the gripper digits conform to the shape of an object and then switches to the fully actuated precision mode, where each joint is individually locked, leading to a fully actuated gripper for handling the grasped object, thus amplifying its payload capabilities. A design concept is presented that combines all planned requirements - a moderate dexterity, a high force and a compact design of the control unit. This concept is based on a frictional locking of the joints via electromagnets. The resulting gripper was rapidly prototyped and tested for the following characteristics: flexibility in operational environments, payload capacity, accuracy and repeatability of operation. This prototype gripper can grasp objects with a force of up to 70N under active control of all degrees of freedom.**

keywords [end-effector, design, grasping, manipulation, actuation, mode-switching]

I. INTRODUCTION

Robotic end effectors are one of the most well researched components of any robotic system built for grasping or manipulation tasks. There are usually two varieties of end effectors, namely: grippers that usually are non-anthropomorphic in nature and are built for very specific tasks, usually consisting of two or three digits and the anthropomorphic type, resembling a human hand to perform human-centric tasks [1]. Industrial end effectors, such as the Barret-Hand Grasper [2] or the various generations and variants of the SDM hand [3], [4], [5], differ from anthropomorphic hands in a way that the design, weight and size of end effectors are independent of those of the human hand. However, this does not mean that these parameters, like weight, are arbitrary, as they play a crucial role in the performance of the grippers [6]. Depending on the application, there can be special requirements. These include the grippers being either a compact, lightweight and simple design for fast production, or a universal application with a differentiated grasping behavior [6]. Grippers can generally be split into two categories. The first being those that are easy to manufacture but specialized for certain tasks and the second being those that are universally designed for a large number of tasks, but are therefore highly complex [7]. The general requirement of a high grip force for industrial grippers often comes along with the disadvantage of them also being heavy [6].

The gripper developed in this work is supposed to be the end effector of the humanoid robot Roboy. In the case of grippers as end effectors for humanoid robots, the requirement for a compact control unit is very high. This can be placed intrinsically in the hand, as with the gripper of the R1 robot [8], or also in the forearm following the model of the human hand, as with [9]. The need for a compact and lightweight actuation unit competes with the requirement of the gripper having a high force and moderate dexterity, which is why so far only one of those aspects can be fulfilled extensively.

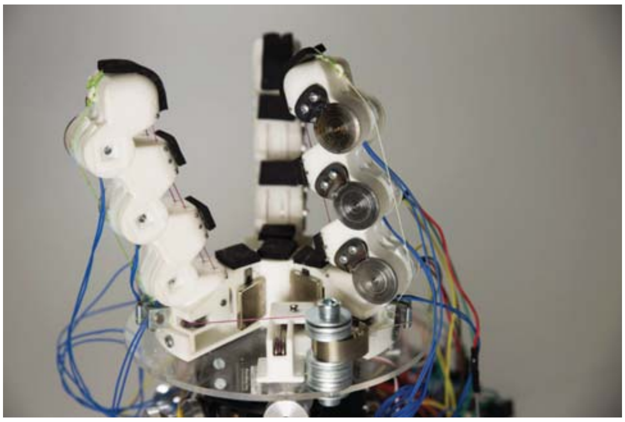

Fig. 1: Prototype of the 3-Finger Gripper. Every joint of the gripper can move independently

A. Need for mode switching

Depending on the positioning of the actuation unit and the requirements placed on its size and weight, different numbers and sizes of actuators can be used, which significantly influence the force and dexterity. A high actuator force is associated with the disadvantage of a lack of compactness and high weight due to the limited energy density attainable [10]. A high force therefore implies a large, heavy control unit [6]. There is also a trade-off between the number of actuators (influencing the dexterity) and weight [11]. Strong and dexterous robotic grippers, as in the case of the Shadow Hand with pneumatic actuators, typically includes the use of a large control unit [12]. This points out the relevance of this work, which focuses on how to realize a dexterous actuation with only one motor, thus resulting in a compact actuation unit.

The number of degrees of freedom (DOF) and the number of actuators (Degree of Actuation - DOA) as well as the ratio of DOF to DOA, are relevant topics for the design of robotic end effectors. The number of degrees of freedom is defined by the number and type of joints in the system. Basically,

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the number of degrees of freedom correlates directly proportional to the passive mobility of the system. Active degrees of freedom are defined when the movement of a degree of freedom can be controlled independently by an actuator. If the number of degrees of freedom is equal to the number of actuators, all degrees of freedom are actively controlled and one speaks of a fully actuated system. These systems have the most diverse movement possibilities, which are limited only by the number of degrees of freedom [13]. According to Townsend [2], it is precisely this active control of each individual DOF that is the strict mathematical definition of Dexterity, which is why we want to create a gripper which can be fully actuated.

However, this has the disadvantage of necessitating a complex and space-intensive control system with many actuators [13], like the Shadow hand [14].

For simple end effector grippers which prioritize low complexity and compactness of design, a low number of realizable degrees of freedom is required [15]. This leads to simple grippers with reduced mobility and performance limited to special grasping tasks [16]. This performance is sufficient for individual industrial robots with only one special grasping task. With generalized industrial grippers, however, which place high demands on the functionality and especially on the gripping compatibility of multiple objects, this often leads to performance losses.

This research's answer to this problem is the introduction of underactuation [17]. When a device is underactuated, the number of degrees of freedom is greater than the number of actuators, resulting in the passive control of the degrees of freedom and joints [10]. Compared to a fully actuated system with few degrees of freedom, this approach has the advantage of enabling a natural grasping behavior with a high adaptivity to the object to be gripped, which can otherwise only be realized with the use of multiple actuators and degrees of freedom. In addition, a simple control logic and a natural gripping movement similar to that of the human finger can be created [18], which is what makes underactuation interesting for our gripper design.

However, the underactuated adaptive case also means that the system, for one actuator, always follows exactly one trajectory defined by the design with minimal energy [5]. However, this means that only one actively controllable trajectory, i.e. one type of grasping, can be realized per actuator [19] often called a ”Power Grasp” [10]. By using a minimum number of actuators, a natural grasping behavior with high passive mobility and functionality can be created, but not a system with high dexterity, which requires differentiated grasping cases and therefore a fully actuated system. In addition, grasping cases, which require a higher precision, re difficult to realize.

In order to combine the advantages of both underactuation and full actuation, a mechanism is introduced in this work, which allows a switch between the two modes of actuation. The core element of the system is an electromagnet, which acts like a passive actuator, and allows to transform the underactuated gripper with only one motor to a fully actuated gripper without increasing the number of motors.

II. CONCEPT DESIGN

A. System requirements

The focus for the gripper is on improving the force along with fulfilling the function of grasping. Also, aspects such as size, weight and compactness play an important role for its design as an end effector for the humanoid robot Roboy or in general for a robotic arm. The challenge and relevance of this work lies in the combination of the set goals and the resulting requirements, as the state of the art shows. It is relevant for all end effector applications, which aim for a high force and high dexterity at the same time. They can be defined as follows:

1) The gripper should be strong enough to grasp and hold things of a weight comparable to a beer case.

2) The grasping behaviour of the gripper should be optimized with regard to a functional but differentiated grasping of a maximum variety of objects.

3) The gripper should have a compact and simple control unit to fulfill its purpose of being an end effector.

For the challenging combination of these three aspects, a basic design concept will be developed. The development of this design concept and its evaluation on the basis of experimental prototyping is the central goal of this work. The aim is to determine whether the design concept will prove itself as a fundamental basis for fulfilling the goals and requirements described above.

B. Technical requirements

In addition to the User requirements, the general conditions and technical requirements of the Roboy project must also be taken into account. The gripper should be actuated via tendons and the actuator itself should be an electrical motor, or a servo depending on cost and availability. The actuation with tendons and electrical motors aims for an ideal indirect force transmission, which allows to relocate the actuation unit elsewhere then inside the joints. Electric motors, furthermore have the advantage of having a good force weight ratio. The technical requirements based on the user requirements are as follows:

1) In order to grasp and hold heavy objects, the gripper should be able to perform grasps with a force of 100N. This requires one or more strong motors, which are normally large and heavy.

2) In order to realize a moderate degree of dexterity, we aim for a fully actuated system, which implies there being as many actuators as DOF.

3) For a compact actuation unit, the number and size of motors should be kept to a minimum.

This places high demands on the actuation system. The key trade-offs that currently exist in the state of the art and that this work is intended to overcome are the compactness of the system, which oppose the goals of a high force, and a certain level of system dexterity.

C. Concept

The overall gripper design with electromagnetic joint locking as the core element is as follows. The gripper comprises 2 or 3 fingers, which are fixed on an abstract palm.

The central design concept introduces a mechanism for a fully actuated system by which the joints of each finger can be actively locked so that they form a rigid unit together with the two phalanges that connect them. This locking is done by means of electromagnets located directly inside each joint itself and attached to one of the two finger links connected by the respective joint.

This kind of indirect actuation of the joints does not lead to a direct control of the joints. However, it does influence the movement that is transmitted to the fingers via the tendon. If all but one joint is locked, the movement can only be transferred to the unlocked joint. This corresponds to the possibility of the active control of any joint, i.e. a full actuation.

III. EMBODIMENT DESIGN

The fingers as the central component of the gripper are all the same and have 3 DOF, and therefore 3 electromagnets each. The DH parameters of each finger are straightforward and are given in Table.I.

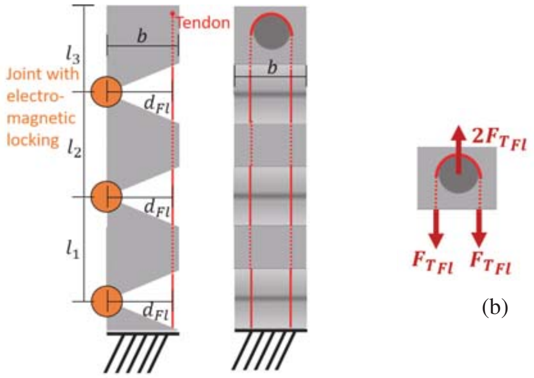
TABLE I: DH Parameters for one finger. In the following $\theta_(i+1)$ is stated as ϕ_i

Link	$A_i(mm)$	$d_(i+1)(mm)$	α_i	$\theta_(i+1)$
i=1	0	0	0	0°
i=2	35	0	0	45°
i=3	35	0	0	45°
i=4	30	0	0	45°

A. Actuation Mechanics

One finger as shown in Fig.2 is controlled exactly by one tendon and thus at most by one motor. As in [20], this tendon attaches to the upper distal end of the end phalanx and is passed through tubes through the other phalanges without contact. At one end the tendon is also connected to the actuator. In contrast to [20], however, the tendon is not fixed at its attachment point at the distal end, but is deflected there via a deflection pulley and, ideally, smoothly downwards through tubes in the two phalanges where it is then either fixed or guided into the next finger. This principle allows the force $F_{T_{Fl}}$ transmitted to the system by the tendon to be doubled according to the forces shown in Fig.2.

Routing the tendon into the adjacent finger allows to further reduce the number of motors. Because of the electromagnet joint locking the whole system is still fully actuated. The mechanism for stretching the finger is realized passively via mechanical spring components, so that no active tendon control with corresponding actuator is necessary.



(a)

(b)

Fig. 2: Schematic concept of the finger. a) model of the finger implementing the electromagnets mechanism, b) tendon forces $F_{T_{Fl}}$ applying on the distal end of the finger

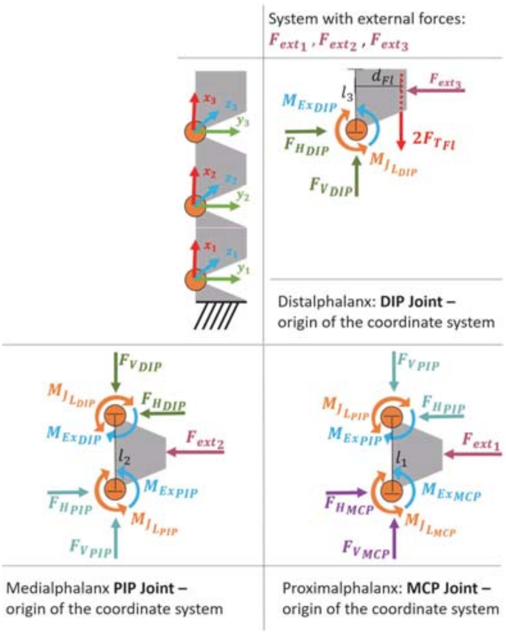


Fig. 3: Static Model of the forces applying on the finger

1) Mechanics: The description of the transmission of motion at the joints due to the forces acting on the finger is intended to explain the design in more detail. For this purpose a simplified time-discrete, quasi-static mathematical description is chosen as shown in Fig.3, neglecting friction. Distal phalanx and DIP-Joint Fig.(3):

$$\begin{aligned} \sum M_{J_{DIP}} : 2F_{T_{Fl}} d_{Fl} - M_{Ex_{DIP}} \\ -F_{ext_3} \frac{1}{2} l_3 \pm M_{G3} \\ = \pm M_{J_{L_{DIP}}} or I_3 \phi''_3 \end{aligned} \tag{1}$$

Medial phalanx and PIP-Joint (3):

$$\begin{aligned} \sum M_{J_{PIP}} &: \pm M_{J_{L_{DIP}}} + M_{Ex_{DIP}} \\ -M_{Ex_{PIP}} - F_{ext3} \cos\phi_3 l_2 &- F_{ext2}\frac{1}{2} l_2 \pm M_{G2} \\ &= \pm M_{J_{L_{PIP}}} or (I_2 + I_3)\phi\,''_2 \end{aligned} \tag{2}$$

Proximal phalanx and MCP-Joint (3):

$$\begin{aligned} \sum M_{J_{MCP}} &: \pm M_{J_{L_{PIP}}} + M_{Ex_{PIP}} \\ &- M_{Ex_{MCP}} \\ -F_{ext3}(\cos\phi_3 \sin\phi_2 &- \sin\phi_3 \cos\phi_2 l_1 \\ -F_{ext2} \cos\phi_2 l_1 &- F_{ext1}\frac{1}{2} l_1 \pm M_{G1} \\ &= \pm M_{J_{L_{MCP}}} or (I_1 + I_2 + I_3)\phi\,''_1 \end{aligned} \tag{3}$$

M_{J_i} is the moment of all forces acting around $Joint_i$, $M_{J_{L_i}}$ is the moment that can be transmitted via the electromagnetic joint locking in $Joint_i$, $F_{T_{Fl}}$ is the tendon force applying on the distal end for flexion, d_{Fl} is the lever arm between $F_{T_{Fl}}$ and the Joint axis, M_{Ex_i} is the moment for extension around the $Joint_i$, F_{ext_i} is the external force acting on the respective $digit_i$, l_i is the length of $digit_i$, I_i is the moment of inertia of the respective $digit_i$ and $\phi\,''_i$ the movement around $Joint_i$, M_{Gi} is the gravitational moment of the respective $digit_i$

2) Magnet mechanism: When the electromagnet is switched on, a corresponding counterpart (hereafter referred to as the metal lock plate) is locked. This metal lock plate is attached to the other finger link, which is now firmly connected to the first finger link by the force F_{MN} transmitted by the electromagnet. The full spectrum of movements that can thereby be realized is clearly shown in 4 in comparison with the underactuated case.

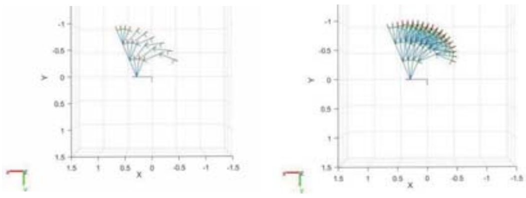


Fig. 4: Comparison of the variety of movement trajectories of a) the underactuated finger without electromagnetic joint locking b) the fully Actuated finger movement with electromagnetic joint locking

A similar principle of locking the joints is also realized in [21] by means of an electromagnet, but with form closure. By this, the locking is limited to discrete positions. At high forces and speeds, the form closure can easily lead to malfunction or even damage to the system, which is why it is not robust. With the gripper for this work, on the other hand, the locking is achieved by frictional locking with the Moment M_{J_L}, as shown in Fig.5.

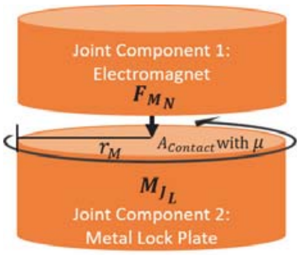


Fig. 5: Frictional locking of the joint via electromagnet resulting in the moment M_{J_L}, F_{M_N} is the normal force of the magnet, which is converted to the moment M_{J_L} with the friction coefficient μ of the surface and the radius r_M of the magnet

$$\begin{aligned} M_{JL} &= \mu \frac{F_{M_N}}{\pi r^2} \int_0^{2\pi} \int_0^{r_M} r^2 d\pi dr \\ &= F_{M_N} \mu \frac{2}{3} r_M \end{aligned} \tag{4}$$

Due to this type of force transmission from F_{MN} to M_{JL}, no arbitrarily high torque M_{JL} can be transmitted, and in the case of the forces acting on the finger being too high, no more locking takes place, but the potential damage to the system can be ruled out. The system is therefore robust at high speeds and high forces. In addition, the joint can be continuously locked and unlocked for any joint angle. For high speeds, this excludes jamming of the joint and leads to great movement flexibility.

IV. DETAILED DESIGN

A. *Finger design*

The detailed finger design as shown in Fig.6 and Fig.7 comprises the mechanism for finger extension, as well as the detailed joint design with the core elements (the electromagnet and metal lock plate) which together form the joint locking mechanism.

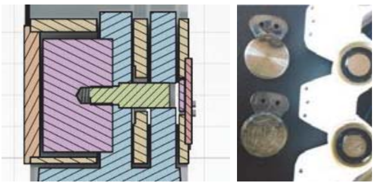


Fig. 6: Joint Design with electromagnets mechanism. From left to right: a) Joint with the electromagnets, b) electromagnets and metal plate

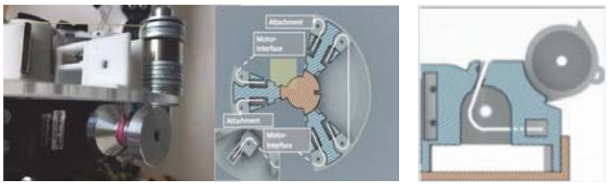
B. *System design*

The detailed design for the whole gripper as shown in Fig.8 focuses on the tendon routing and its connection to the motor, in order to combine several fingers with one tendon and to realize therefore the effect of a reduced number


(a) (b)

Fig. 7: Finger extension mechanism. from left to right a) finger from backwards view with the extension tendon, b) routing of the extension tendon to a spring to enable passive extension

of motors while having a fully actuated system via the electromagnetic control of the joints.



(a) (b) (c)

Fig. 8: Detailed System Design. From left to right clockwise: a) tendon - motor connection, b), c) tendon routing within the gripper

C. Electronics

In order to be able to test the system in a reliable, automated and constant environment with a defined test procedure, a test rig was designed.

The core element of the electronics for the test rig is an Arduino Mega 560, which allows simple control of the system for test purposes. The control hardware consists of the following actuators and sensors shown in Fig.9, through which the Arduino can control the system and receive system information as feedback. This system feedback is either read directly to evaluate the test series or processed by the control unit for the next step.

The electromagnets are controlled via PWM signals and a simple transistor circuit, which allows two modes - on and off. The servo motors are also controlled via PWM signals. Hall sensors within each joint allow to read the joint position via neodymium magnets placed in the shaft, co-axial to the rotation axis. The sensors are read by the Arduino via I2C-communication. The sensor for the motor angle is already integrated into the servo motor. This is also a Hall sensor, which is connected to the microcontroller via a capacitor circuit and is read out by the microcontroller as an analog signal.

The final control of the system is done by the software running on the Arduino. This was designed for the gripper based on a class structure.

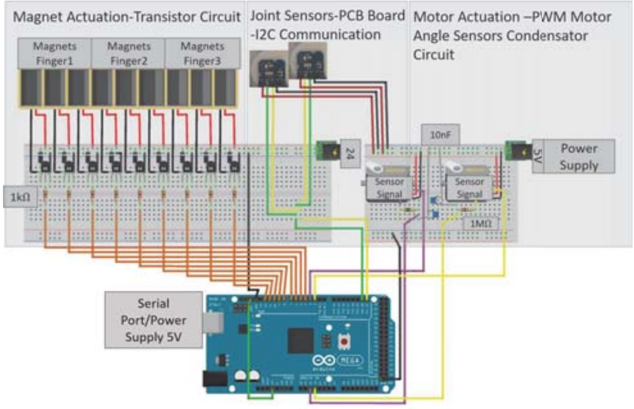


Fig. 9: Sensors and Actuators for Control of the Gripper

V. Testing and Analysis

Firstly, the evaluation should show whether the objectives of maximizing force and achieving differentiated grasping behaviour have been achieved. Secondly, the electromagnetic joint locking mechanism should be examined with regards to its precision and functionality. In addition, the test ”The Form Features and Performance Index” [15] was used for a comprehensive evaluation and the benchmarking of end effectors. This is strongly focused on the functional anthropomorphism of robot hands and goes beyond the objectives defined in this paper. However, this allows the gripper to be evaluated by generally defined reference criteria. The test series results as follows:

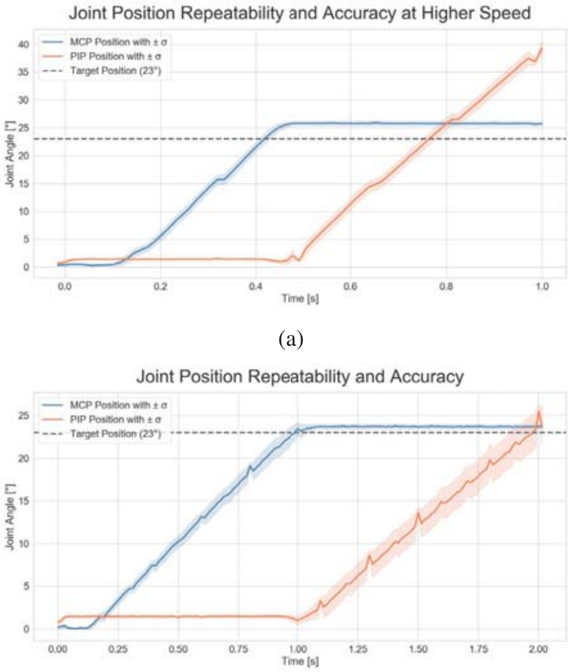
A. Joint Position Precision and Repeatability

The precision of the movement of the individual joints is evaluated by defining the associated minimum coordinates ϕ_i, which in turn determine the accuracy of the finger movement trajectory. A high precision of movement for each joint can be reached by locking the other joints through the electromagnetic mechanism. The level of precision achieved is to be tested by independently moving a certain joint of the finger (here the MCP joint) at a defined constant speed. At a defined angular position $\phi_1 = 23°$ the magnet of the joint is locked and the magnet of another joint (here the PIP joint) is opened, and the MCP moment stops while the PIP joint begins to move exactly at this point of time (see Fig.10). The angle between the two joints is measured constantly.

The critical point of the test is the moment when the joint lock changes. The angle of the joint locked from this moment should remain constant from $\phi_1 = 23°$ and the angle ϕ_2 of the other joint should assume a value of $\phi_2 > 0$ at the moment in which the angle $\phi_1 = 23°$ is detected. The time between the detection of the angle reached $\phi_1 = 23°$ and the mechanical change of the joint lock is the latency of the magnetic mechanism and determines how fast and precisely the joints can be controlled alternately.

In the graph in Fig.10 the higher speed (see Fig.10 (1)) shows a greater angular deviation of $\Delta\phi_1 = 3°$ than in the experiment with the slower speed with angular deviation $\Delta\phi_1 = 1°$ (see 10 (2)).

This difference is due to the latency of the locking mechanism. If the angle of the MCP joint reaches $\Delta\phi_1 = 23°$, the signal to close the MCP joint and to open the PIP joint is given almost simultaneously in both systems except for the sequential software commands. Both graphs in Fig.10 show that the latency between the actual opening and closing is approximately 0.05 seconds due to the mechanics of the locking mechanism. At a higher speed, a larger joint angle is covered during this time, which means that the joint comes to a standstill for a higher angle.



(a)

(b)

Fig. 10: Joint Position Precision. a) Test result of a good accuracy of the joint position for several test runs at higher speed, b) Test result of a very high accuracy of the joint position for several test runs at lower speed meaning a very small joint switching latency

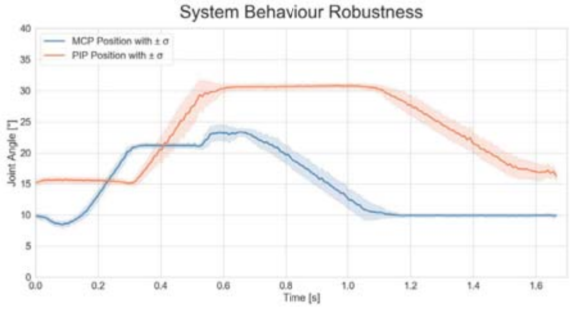
For the test runs, the angle values of the two joints should be as close as possible for a high repeatability of the system.

Looking at Fig.10, it becomes clear that as the number of test repetitions increases, the dispersion of the system increases to an angle range of $\Delta\phi = 1°$ for standard deviation for the respective time, which is mainly due to an inaccuracy of the angle sensor and to the inaccuracy of the system itself due to static friction. Overall, the result can be interpreted as such: The closing mechanism has a very high precision with a minimum latency of 0.05 seconds. For very high speeds, however, this can lead to a slight deviation of the desired angle, which is why the system has a higher precision for slower speeds.

B. Failure analysis

This test should give a statement about how often a certain result can be reproduced without the system failing due to lack of stability or loss of function due to undefined system behavior. This behavior is mainly determined by the locking of the joints. Here a certain movement cycle is defined which is to be reproduced for a maximum number of repetitions. The concrete motion cycle is as shown in Fig.11. Due to the availability of only two joint angle sensors, only the two proximal joints could be included in the test.

Due to a defect of the sensors, which caused a failure of the measurement after an indefinite time, a maximum of 380 cycles was achieved. The results of the graph show a precise behavior, with only a small deviation of 1° to 3° from the desired angular position. For multiple repetitions, however, there is again a certain dispersion of the system, which can also be described as hysteresis and, as already mentioned, can be attributed to static friction, tendon elongation and angle sensor inaccuracies. For each change of flexion and extension, the mass inertia causes the angle of the MCP joint to first deflect in the opposite direction before the system goes through the desired motion sequence. Overall, however, the experiment clearly shows that the system behavior is reproducible with only minor deviations for multiple repetitions. This shows that the electromagnetic locking mechanism with frictional locking achieves a flexible movement behavior with high stability and precision.



(a)

Fig. 11: Failure analysis. Test result of 380 successful repeats of the predefined movement: Flexion of the MCP joint up to 20°, flexion of the PIP joint up to 30°, extension of the MCP joint up to 10°, extension of the PIP joint up to 15°

C. Payload

The actual maximum force of the gripper should be determined for the strongest gripping cases. The coarse human force, whose configuration corresponds to the cylindrical and spherical “Power Grasp”, is up to 50 kg. However, it is to be expected that the limited nominal torque of the servomotors themselves will prevent the target of holding 10 kg from being reached.

In the test, an object is attached to a load cell with a tendon , which is statically attached to a device. This is placed in the middle of the gripper (see Fig.12). The gripper is then

Fig. 12: Test setup for testing the payload for the cylindrical and spherical power grasps

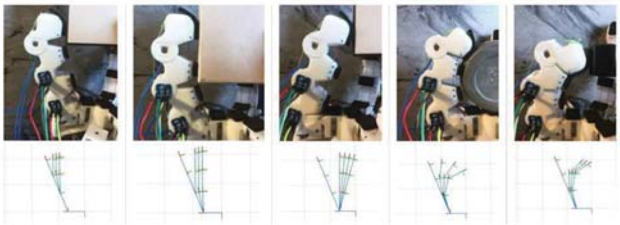


Fig. 13: Result of a very dexterous movement of the finger due to the electromagnets mechanism

closed with full motor power and all joints, except the DIP joints, are locked at the end. These are the last to be closed in order to continue transmitting the full power of the motor. As soon as the object is gripped by the gripper, the maximum tensile force for which the gripper can hold the object is measured via the load cell. This tensile force corresponds to the weight force of an object gripped from above, minus the self-weighting force of the test object, which was selected as low as possible.

The device shown in Fig.12 continuously increased the tensile force on the object and thus achieved a maximum force of $F_{max} = 70N$ for the cylindrical case and $F_{max} = 62N$ for the spherical case. The lower force with the spherical power grasp can be attributed to the size of the object, as the gripper can apply more force as soon as the fingers are more curved. This generally means a higher force for smaller objects, which can also be observed in human gripping behavior. In both gripping cases, it was also observed that once the magnets were released during the grip, both the stability of the grip and the force decreased significantly. This indicated that the electromagnetic joint lock provides the great advantage of additional force and stability.

D. Fully Actuated Grasping

In general, the electromagnets mechanism concept should allow all joints to be actively and independently controlled. This behaviour could be validated, as shown in Fig.13. Overall, however, the temporal sequence is limited. Due to the magnetic mechanism, those joints which are controlled by the same motor cannot be actively controlled simultaneously, independently of each other, but only one after the other. This time limitation must be taken into account when implementing the control logic.

E. FFP Index score discussion

In order to evaluate "Form and Features" from the test by Sureshbabu et al. [11] as well as "Performance" for a meaningful comparison of the gripper, the criteria introduced in this test were evaluated on the gripper.

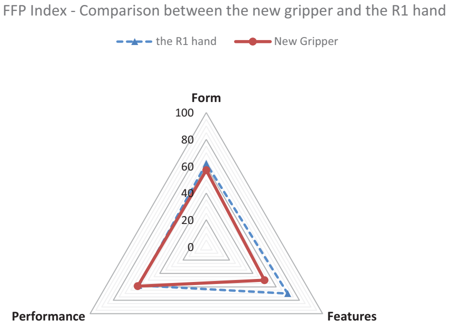


Fig. 14: FFP Index. The score of the proposed gripper with electromagnetic joint locking compared to the score of the R1 hand. The gripper performs better than the R1 hand with lesser features.

Fig. 15: Performance Test from the FFP Index. 62 out of 63 successfully performed prehensile grasping tasks

The "Performance" of the gripper was mainly evaluated by a defined test set of 63 prehensile grasping tasks from Sureshbabu et al. [11], from which the gripper performed 62 successfully (see Fig.15).

The overall score of the gripper for the Form, Features and Performance index (see Fig.14) in comparison to the score of the R1 hand [8] shows that it has a better "Performance" than the R1 hand, despite having fewer "Features". However, in addition to the prehensile grasping tasks, the "Performance" test also includes non-prehensile grasping tasks, in-hand manipulation and human-like gestures, which the gripper could not perform as well. The reason is a lack of a proper control of the gripper, which is currently being improved upon.

"Form" describes the level of anthropomorphism the hand attains. The gripper was not designed as an anthropomorphic imitation of the human hand, and hence scored lower than the R1 hand in this section.

VI. CONCLUSION AND FUTURE WORK

A. Summary

The basic design principle of locking by means of electromagnets results in several decisive advantages. First of all, all defined requirements which had originally contradicted each other (based on research on the state of the art) can be fulfilled. With the electromagnets the system can be fully actuated which allows a high dexterity. Nevertheless, the complexity of the control itself is only slightly higher than that of underactuated systems, since at most only one motor per finger must be controlled. Due to the reduced number of motors, motors with a higher nominal torque can be selected. In addition, by locking all joints when the gripper is closed around an object, the gripper can be completely modified into a rigid unit. This creates an additional force and stability of the gripper.

Moreover, due to the frictional locking of the joints, the system is very robust and can withstand high forces acting on the system. If the forces are too high for locking the joint, the gripper acts like an underactuated gripper, which is a suitable mode for power grasps where force and the adaptability to the object is more important than a dexterous actuation of the gripper. In addition, the design represents a more general solution for the compromise between size and weight, and force and dexterity. The principle of decoupling actuators from active degrees of freedom, can be further developed and transferred to any type of robotic system with different requirements.

B. Improvements

In order to maximize the force and achieve a final compact design as intended by the basic design concept, the servo motors and the test bench should be replaced by motors with better performance embedded compactly in the gripper. In addition, it makes sense to develop a solution for force measurement integrated in the gripper instead of the external load cell for a more defined force measurement, which will also lead to a better control. Lastly, the underactuated movement behavior should be optimized so that it corresponds to the natural motion trajectory of humans and shows a high adaptability to the object. The closing behavior can be adjusted by changing the stiffness of the joints, for example by using springs with different spring constants in each joint. With such a design, the underactuated grip mode can be optimized and the fully actuated mode can only be used for precision grips. The technology is also intended to be transferred to an anthropomorphic hand and tested for ease of technology transfer given size and shape constraints.

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