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DESIGN AND DEVELOPMENT OF TWO CONCEPTS FOR A 4 DOF PORTABLE HAPTIC INTERFACE WITH ACTIVE AND PASSIVE MULTI-POINT FORCE FEEDBACK FOR THE INDEX FINGER

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ABSTRACT

This research aims to develop a portable haptic master hand with 20 degrees of freedom (DOF). Master hands are used as haptic interfaces in master-slave systems. A master-slave system consists of a haptic interface that communicates with a virtual world or an end-effector for tele-operation, such as a robot hand. The thumb and fingers are usually modeled as a serial linkage mechanism with 4 DOF. So far, no 20 DOF master hands have been developed that can exert perpendicular forces on the finger phalanges during the complete flexion and extension motion. In this paper, the design and development of two concepts of a portable 4 DOF haptic interface for the index finger is presented. Concept A is a statically balanced haptic interface with a rolling-link mechanism (RLM) and an integrated constant torque spring per DOF for perpendicular and active force feedback. Concept B utilizes a mechanical tape brake at the RLM for passive force feedback. The systematic Pahl and Beitz design approach is used as an iterative design method.

1. INTRODUCTION

Human hands can grasp objects with high grasping forces and are capable of doing skilled dexterous manipulations with high precision, like the handling of tools. These characteristics make them excellent manipulators. Skillful manipulations of human hands are commonly needed in extreme environments, for example in radioactive environments or outer space. Here, human presence can be avoided with master-slave teleoperator systems. A master-slave teleoperator system consists of a master and slave device, where the operated master device transfers the commands to the remote slave device. A slave device is more often a five fingered robot hand with 4 degree of freedom (DOF) per finger. Therefore, there is a need for an appropriate master device that can be operated by the human hand. Hence, a device is needed that can measure the fingers' motion and that can exert a realistic feedback force. In this paper such a device or haptic interface, is named a "master hand."

Three other promising fields for the use of a master hand are; (1) interacting with a virtual world, because virtual reality is used in applications such as virtual surgery or virtual support in computer-automated design; (2) human hand rehabilitation and; (3) haptic assistance.

The control theory of master-slave systems can be distinct in two classes; the impedance and admittance controlled devices [1]. Impedance control is when the operator moves the haptic device and the device will react with a required force. The operator will feel the mass and friction of the device. These unwanted influences can be made very small with a careful mechanical design. The device should have high backdrivability or the capability of free movement when no feedback forces are desired, like the haptic interfaces of the PHANToM series [2]. Admittance control theory is valid when the operator exerts a force on the haptic interface and the device will react with the needed displacement. Admittance control usually results in robust mechanisms, capable of displaying high stiffness and high forces. This research will focus on an impedance controlled master hand, which requires a careful mechanical design. This should result in a lightweight design with low friction forces, low inertias, high stiffness, no play and high backdrivability.

Haptic interfaces can be divided in grounded and portable devices. Grounded devices, such as the PHANToM, limit the range of the operators' freedom of motion, but are capable to simulate fixed objects. A portable haptic interface allows the most natural type of interaction because the freedom of the operators' motion is less limited. The portable haptic interface can only simulate fixed forces in combination with a grounded device. This research aims to design a portable master hand that is fixed on the hand of the operator.

Several portable master hands have been developed and patented until now. CyberGrasp is an example of a commercially available master hand, which can exert feedback forces during flexion at five fingertips [3]. It consists of an exoskeleton mounted on the dorsal side of the hand and uses cables for force transmission. The Rutgers Masterhand II is an exoskeleton mounted on the palm side of the hand and can exert feedback forces against flexion at four fingertips [4]. The Sensor Glove II can exert feedback forces on all finger phalanges during flexion and extension of the fingers [5]. The forces are not perpendicular on the finger phalanges and the mechanism encounters friction problems due to friction in the cables. The safe passive force feedback principle is applied to the Multi-Fingered Exoskeleton Master Hand [6]. The exoskeleton consists of an elastic link mechanism and clutch, which enables passive force feedback at the three fingertips. Recently, a new master hand is presented [7]. The exoskeleton follows the movement of the finger with a position sensor. The exoskeleton is blocked when a virtual object is encountered. It and can only exert feedback forces at the fingertips. So far, no developed or patented master hands are capable of exerting forces, perpendicular on the finger phalanges, during the complete flexion and extension motion.

In this research, the systematic Pahl and Beitz design approach is used as an iterative design method for designing a haptic interface [8]. The biomechanical modeling of the human hand is described in section 2. In section 3, the design requirements are stated after an inventory from which the design problem is abstracted and a functional structure is defined. Working structures for the sub-functions of the functional structure are created and concepts are developed. Two suitable concepts are chosen in section 4. Sections 5 and 6 describe the embodiment design stage and evaluation for the first concept A. Sections 7 and 8 describe concept B. In section 9, a general evaluation method is proposed for measuring the performance of a haptic interface. A conclusion is presented in section 10 followed by the future works.

2. BIOMECHANICAL MODELING

The human hand with its motor control is a sophisticated and versatile organic structure for manipulation of the environment. Many biomechanical studies have been carried out for a better understanding of its functions. A human hand is usually modeled as a serial linkage mechanism with 4 DOF per finger, with the so called DIP, PIP, MP joints as acronyms, see figure 1. The MP has 2 DOF and is divided into the MP1 and MP2 joint for respectively the flexion/extension and adduction/abduction motion. In this study the joints are assumed to be precise revolute joints. The relation in movement between the PIP and DIP joints is not taken into account, because this relation is often not used in the PIP and DIP joints of slave robot hands.

An important design parameter for realistic force feedback is the required perpendicular feedback force on the finger phalanges during flexion and extension, as grasping studies of Cutkosky and Howe showed [9].

Experiments are carried out to determine the maximum voluntary contraction (MVC) expressed in joint torque values of the index finger. Therefore, the torque of the finger joints during flexion/extension and adduction/abduction of two male and two female subjects is measured. The average of the values is taken as MVC value. In table 1 the average measured values are given of the male and female subjects. The result of the experiment shows that the torque distribution of flexion and extension is asymmetric. Wiker et al. [10] performed a study of the relationship between fatigue during grasping as a function of force magnitude, rest duration and progression of the task. Fatigue for precision grasping and shifting of the force perception occurred at 25%MVC and higher, but was effectively reduced at low forces below the 15%MVC. Therefore, 15%MVC is the design parameter as force or torque magnitude for a master hand device.

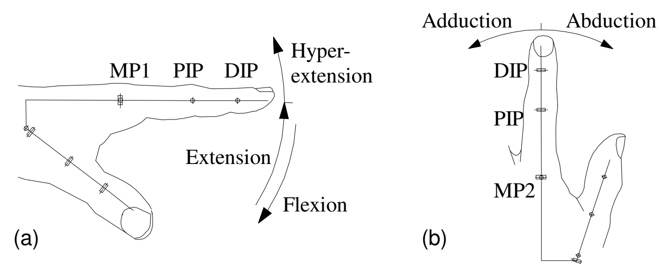


Figure 1: The human hand with a detailed view of the index finger: (a) side view, (b) top view.

Table 1: Measured Torques of the Index Finger Joint.

Joint	MP1		PIP		DIP		MP2	
Motion	Flex	Ext	Flex	Ext	Flex	Ext	Add	Abd
♂ [Nm]	2.05	1.30	0.95	0.6	0.70	0.35	1.60	1.30
♀ [Nm]	1.20	0.55	0.55	0.45	0.35	0.15	1.15	0.85
MVC [Nm]	1.63	0.93	0.75	0.53	0.53	0.25	1.38	1.08
15% MVC	0.24	0.14	0.11	0.08	0.08	0.04	0.21	0.16

Table 2: Important Design Requirements.

Geometry	Device mounted on dorsal side of the hand	
	Device fits average hand size	
Kinematics	4 DOF per finger	
	Full hand closure with exoskeleton	
	Rotational resolution;	< 0.5°
	Finger end-tip resolution;	0.25 [mm]
Forces	Perpendicular on finger phalange	
	Capable of exerting 15%MVC or more	
	High backdrivability during free finger motion	
	Friction forces;	< 0.1 [N]
	Force feedback bandwidth;	> 50 [Hz]
	Low weight;	< 0.3 [kg]
Control	Easy to control	
Production	One prototype for laboratory research	

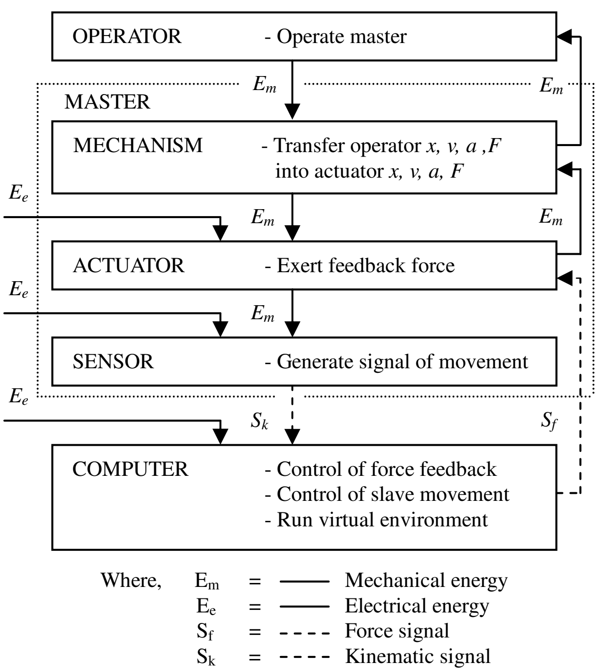


Figure 2: Function structure of the design problem.

3. DESIGN REQUIREMENTS, FUNCTION STRUCTURE AND ABSTRACTION

3.1 Design Requirements

The most important design requirements are listed in table 2 [9,10].

3.2 Design Abstraction

Abstraction of the design problem, when using the Pahl and Beitz design method, is necessary for identifying fictitious constraints and to eliminate all restrictions. The abstraction for this design problem is stated by the authors as: "Design a portable force feedback device for the human hand, in such a way that the device is easy to control and exert safely sufficient feedback forces, perpendicular on finger phalanges for all degrees of freedom, for laboratory research."

3.3 Function Structure

Figure 2 shows the function structure that is determined by the design requirements and it gives the relationship between the inputs and outputs of the device. The structure of the haptic interface consists of three sub-functions. The first function is transferring displacement, velocity, acceleration and force by a mechanism. The second function is exerting feedback force by an actuator. Finally, the sensor senses the movement and creates a signal.

4. CONCEPTUAL DESIGN

Several solution principles are presented in the conceptual design phase to fulfill the three sub-functions and are placed in a morphological matrix. Four new initial concepts are generated with the matrix, which are not patented and differ from the current developed master-hands. The concept that is selected by a value analysis is discussed in this section.

4.1 Mechanism

The transformation by the mechanism should have the property of high backdrivability. Therefore, linkage mechanisms, gears with low gear ratios, cable drives, pulleys, belt drives, levers and rolling-link mechanisms are proposed.

The value analysis method resulted in a rolling-link mechanism (RLM) solution [11]. The RLM can exert forces, under constant angle and almost perpendicular on the finger phalanges during the complete flexion and extension motion. The RLM has the characteristics to have low friction, roll smoothly and rotate without stick or slip. The RLM solution can be actuated by two actuating principles, which will be discussed in section 4.2.

4.2 Actuator

Until now, no actuators exists for actuating 1 DOF with a needed higher bandwidth of 10 [Hz] and with a needed power-to-weight and/or -size ratio for direct mounting on the human hand [10]. Brushless DC-motors are appropriate actuators for a haptic device. They have high backdrivability, low friction, low inertia and are controllable at torque. A brushless DC-motor in combination with a backdrivable cable drive creates a higher output torque. A cable drive transmits torque from the motor with a pre-tensioned cable reduction to a pulley. The weight and size of four motors with cable drives, which are needed for actuating 4 DOF, is too big for direct placement on the hand. A remote actuator module with a force transmission cable to the exoskeleton can overcome this limitation. A disadvantage is that a force transmission cable will induce unwanted friction forces, which will mask the force resolution. The friction force also limits the backdrivability.

Friction forces between the inner cable and outer cable depend on the friction coefficient, curvature of the cable and tension on the inner cable. To make use of the freedom of the operators' hand at least a cable length of 0.5 [m] is needed, because this is a suitable working range of the human hand. A cable can only transmit forces in one direction. A cable in combination with a spring can be used to transmit forces in two directions, this result in tension on the inner cable that causes higher friction forces.

Two actuating principles are presented; (1) an actuating principle for active force feedback and; (2) an actuating principle for passive force feedback. These principles differ in functionality. Active force feedback allows the operator to feel object stiffness and to manipulate the object. The stiffness display is limited, because no hard-contact simulation is possible. The actuator could cause injuries to the operator. Passive force feedback allows hard-contact simulation of an object. The actuator cannot exert forces on the finger phalanges and therefore secures the operators' safety. No active manipulation is possible and the operator cannot feel the stiffness of the object.

4.3 Sensor

Only displacement sensors are taken into account for this impedance controlled haptic interface. The sensors should be as accurate as necessary. Non-contact sensors are chosen. The moving part should have a low mass and small dimension to avoid friction and inertia.

4.4 Concepts

Two concepts, concept A and B, with a RLM in the exoskeleton are proposed. Concept A is a statically balanced haptic interface, consisting of an actuator module and a RLM exoskeleton with an integrated constant torque spring for perpendicular and active force feedback [12]. Concept B utilizes a mechanical tape brake at the RLM for passive force feedback.

Concept A consists of; (1) an actuator module; (2) a flexible cable and; (3) an exoskeleton, see figure 3a. The actuator module consists of a brushless DC-motor that drives a pulley by a pre-tensioned cable drive. As a result, a backlash free, low friction and back drivable gear is created. A drum with a constant torque spring is fixed to the pulley, which creates a constant positive moment on the pulley. A single force transmission cable with a flexible outer cable connects the pulley of the actuator module and the circular link of the exoskeleton. The circular link is fixed directly on the finger phalange and rotates about the finger joint. A cable and an opposite placed constant torque spring connect the circular link and drum to achieve a RLM. The drum with constant torque spring creates a negative moment on the circular link. The radius of the pulley, circular link and drums are equal. Therefore, a statically balanced system is accomplished. The force transmission cable is fixed directly on the finger phalange and pulley, which results in simple kinematics.

Concept B consists of; (1) an actuator braking module; (2) a flexible cable and; (3) an exoskeleton, see figure 3b [13]. The actuator braking module consists of a DC-motor that pulls a brake cable. A flexible outer cable guides the brake cable to the RLM exoskeleton. A tape brake is created by looping the cable around the small drum of the RLM.

Concepts A and B are developed into realistic prototypes in the embodiment design phase. This will be discussed in the next sections.

5. CONCEPT A

The detailed design of concept A is shown in figure 4 and 5. Figure 4a, b and c shows the exoskeleton on a stretched and bent finger model. The exoskeleton is fixed on the dorsal side of the hand and finger with plastic fittings and straps. The straps limit the operators' freedom of finger flexion like a glove. Figure 4d shows the RLM of the MP1 joint with the force transmission cable. An exploded view of the RLM with its main components is shown in figure 4e. Two constant torque springs for constant torque spring motors, of the type A 3X51-20004 and two steel RLM cables with a diameter of 0.54 [mm] connect the circular link and spring drum to realize the rolling-link principle [14]. The circular links rotate about the finger joints. The RLM is capable of exerting a constant torque on the joint with a smooth and low friction motion. The two springs with a total mass of 1.2 [g] can exert total a torque of 0.156 [Nm] against extension of the finger, which is more than the requirement of 15%MVC. The drums rotate on a brass axis with two 3-6-2.5 [mm] miniature bearings [15].

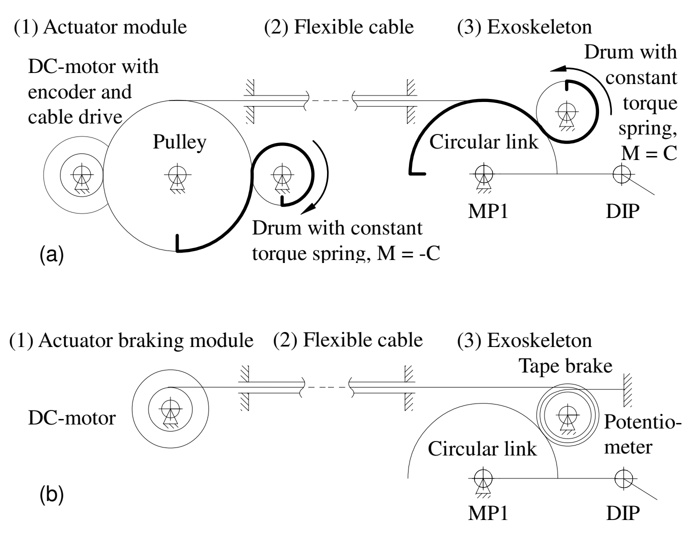


Figure 3: Actuating principles of the concept designs: (a) Concept A - statically balanced RLM for active force feedback, (b) Concept B - RLM with mechanical tape brake for passive force feedback.

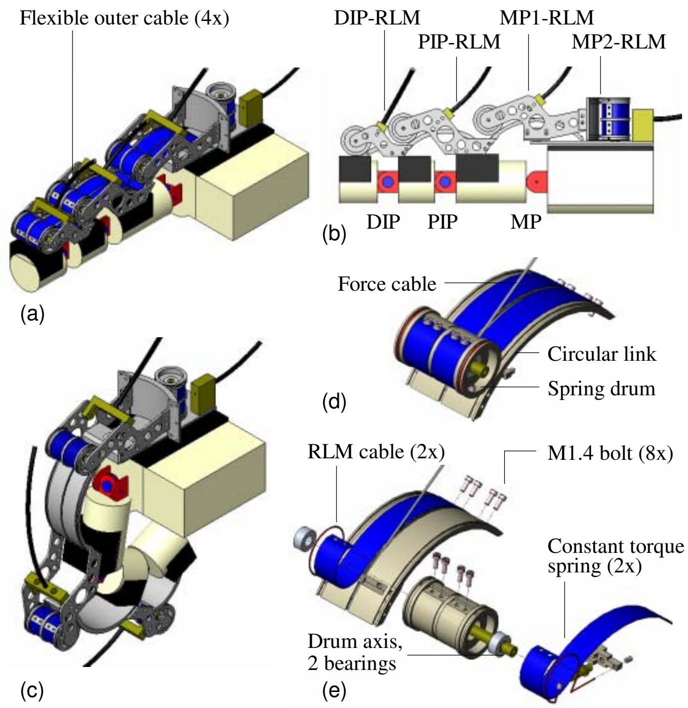


Figure 4: Concept A: (a) exoskeleton with stretched finger model, (b) exoskeleton with bent finger, (c) side view, (d) RLM with force transmission cable, (e) exploded view of the RLM.

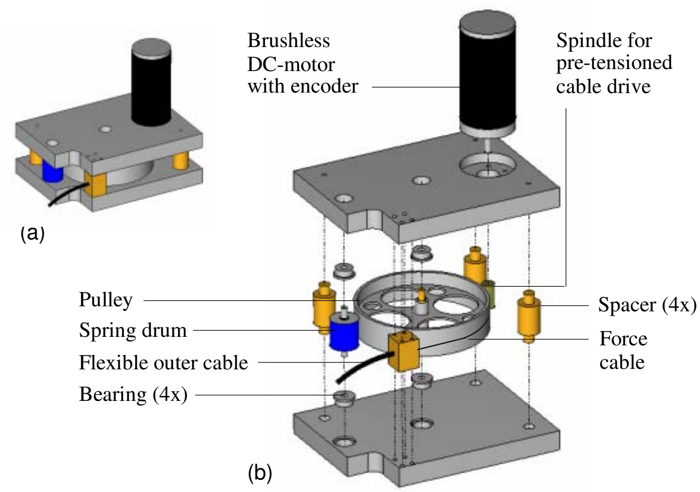


Figure 5: Concept A: (a) actuator module, (b) exploded view of actuator module with its components.

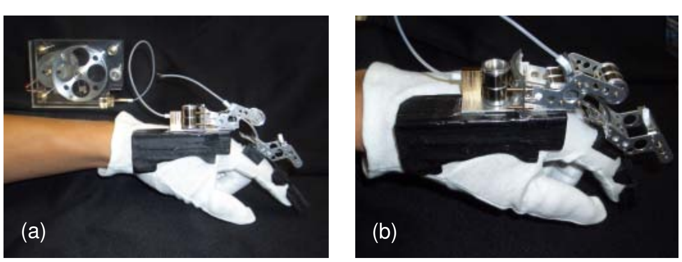


Figure 6: Manufactured prototype of concept A: (a) side view of the actuator module, flexible cable and exoskeleton, (b) exoskeleton with assembled MP joint.

The frame, spring drum and circular link parts are made of aluminum. The actuator module is shown in Figure 5a. An exploded view with its main components is shown in figure 5b. The encoder has an accuracy of 0.18° and is an integrated part of the 20 [W], 15.6 [mNm], Maxon EC 22 brushless DC-motor [16]. The 0.7 [mm] diameter plastic coated force transmission cable has a steel core cable of 0.5 [mm] diameter. The flexible outer cable is made of Teflon, for a low friction sliding contact. The inside diameter is 0.9 [mm] and the outside diameter is 1.4 [mm]. Figure 6a and b shows the manufactured prototype of concept A.

6. EVALUATION CONCEPT A

6.1 Kinematic Characteristics

The rotational resolution of the finger joints is lower than the design requirements. The used potentiometers have an accuracy of 0.18°. With a transfer ratio of 10 for the cable drive, the angular resolution of the finger joint is improved up to 0.02°.

6.2 Dynamic Characteristics

Test results showed that the cable friction influence the dynamic characteristics negatively. Therefore, experiments are carried out; (1) without and; (2) with flexible outer cable to measure the influence. An encoder is placed directly on the MP2 joint of the mechanism. A finger movement of maximum amplitude and speed generates the input signal of the MP2 joint. Both angular position signals are plotted in one graph as function of the time. Figure 7a shows that no significant delay occurs when using no flexible outer cable. Although, using a flexible cable results in a delay time of 0.01 [s] and positional error of 2° as figure 7b shows.

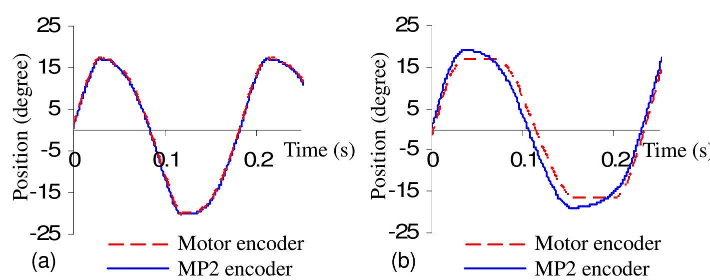


Figure 7: Graph of angular position of motor and MP2 encoder as function of time: (a) without outer cable, (b) with outer cable.

Table 3: Friction forces in the system

Configuration	Friction force [N]
System without flexible outer cable (1, 3)	0.38
DC-motor with cable drive (1a)	0.17
Actuator module mechanism and exoskeleton (1b, 3)	0.21
System with flexible outer cable (1, 2, 3)	1.42 ~ 3.87

6.3 Force Characteristics

Friction forces are exerted perpendicular on the finger phalanges during free finger motion and can be felt by the operator. The friction forces in the system are measured by experiments. The friction force in the complete system is equal to the sum of all friction forces caused by; (1) the actuator module; (2) a 0.5 [m] length flexible outer cable and; (3) the exoskeleton. The actuator module is divided in; (1a) a DC-motor with cable drive and; (1b) a pulley and spring drum. An overview of the friction forces in the system with and without flexible outer cable is shown in table 3.

Without outer cable and DC-motor, the friction forces for the complete mechanism are constant and 0.38 [N]. When adding the flexible outer cable in stretched condition, the friction force is 1.42 [N]. The friction force is variable and increases when curvature of the cable occurs up to 3.87 [N] for a 360° curvature.

The flexible outer cable creates unwanted high and variable friction forces, which makes impedance control impossible. More research has to be carried out to overcome the problems of the friction forces to make this concept more liable.

7. CONCEPT B

The detailed design of concept B is shown in figure 8. Figures 8a and b show the exoskeleton on a stretched finger model. The exoskeleton is fixed on the dorsal side of the hand and finger with plastic fittings and straps. The straps limit the operators' freedom of finger movement like a glove. Figure 8c shows the RLM of the MP1 joint with the spacers and brake cable. An exploded view of the RLM with its main components is shown in figure 8d. Three RLM cables with a diameter of 0.54 [mm] connect the brake drum and circular link to accomplish the rolling-link principle. The frame and circular link parts are made of aluminum. The brake drums are made out of plastics to reduce inertia and weight. The drum is fixed on a brass axis. The axis rotates on two 3-6-2.5 [mm] miniature bearings, which fit into the frame. A smooth and low friction motion of the RLM is accomplished for every joint. The brake drum is equipped with a steel brake ring for increased breaking performance. The tape brake mechanism consists of a steel cable with a diameter of 0.5 [mm] that is looped one time around the steel brake ring. The brake cable is guided through two spacers. The end of the brake cable is fixed to one spacer. The part of the brake cable, or the inner cable that is not in contact with the steel brake ring, is coated with plastic and has an outer diameter of 0.7 [mm]. The flexible outer cable is made of Teflon, for a low friction sliding contact. Maxon RE 25 DC-motors with 20 [W] and 20.6 [mNm] are used for actuating the brakes [16]. The actuators pull the brake cables by a lever mechanism and are placed in the actuator brake modules. A force of 2 [N] is exerted on the brake cable, which is sufficient for creating the 15% MVC torque.

The rotational position of the finger joints is measured by potentiometers located at the drum axis. Figures 8a and b show the positioning of the potentiometers on the frame. The Murata PVS1A103A01 potentiometers have an accuracy of 0.5° and a rotational motion range of 333.3° [17].

The brake of a desired joint is actuated to lock the movement of the corresponding RLM when a virtual object is touched. The locking of the relevant RLM is depended of the phalange that touches the object. Due to the locked RLM, no rotation of the relevant finger joint is possible. The circular links make it possible to exert a perpendicular force on the finger phalanges during the complete flexion and extension motion. The operator will sense a virtual object. The brake is released when the operator moves away from the virtual object.

The brake allows some extension movement of the finger, due to the low stiffness of the flexible outer cable. Therefore, the operator can move the finger away from the object. The brake is released when a rotation of 0.5° is sensed at the potentiometer located at the brake drum for a smooth and low friction movement. Therefore, no strain gauges are required for sensing the force direction to cancel out the braking command, which allows a less complex structure of the device [18].

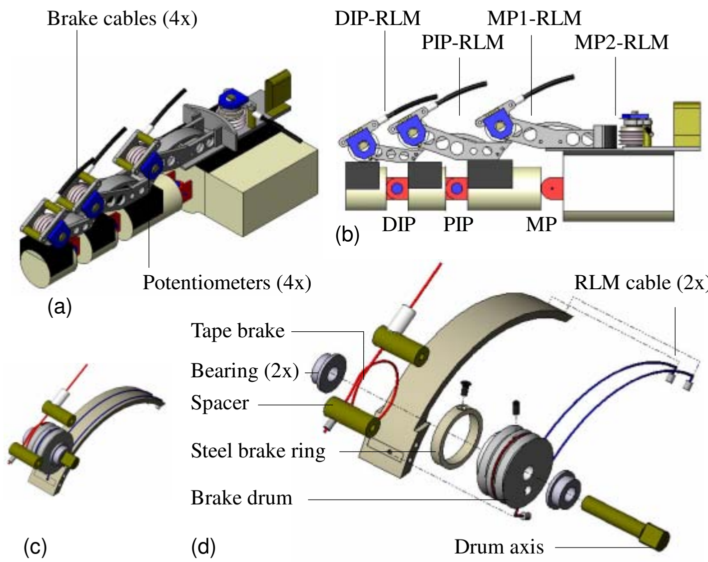


Figure 8: Concept B: (a) exoskeleton with stretched finger model, (b) side view, (c) RLM with brake cable and spacers, (d) exploded view of the RLM with its main components.

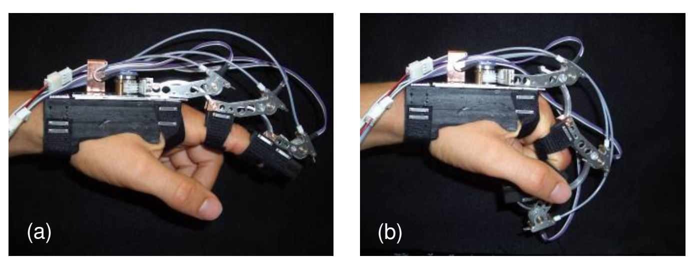


Figure 9: Side view of the concept B prototype: (a) relaxed stretched position, (b) full flexion.

Figures 9a and b show the side views of the left index finger with the developed exoskeleton in stretched and bent finger position. Top views of the left hand index finger with exoskeleton in adduction and abduction finger position are shown in figures 10a and b. A close-up view of the RLM with tape brake of the MP joint is shown in figure 11. The developed exoskeleton for the index finger fits well on the operators' hand.

The weight is 60 [g], which allows fast natural finger movements. A graphical user interface (GUI) for interaction with a virtual world is created in C++. The virtual world consists of a simple finger model with 4 DOF and a straight wall and circular object for touching. The finger phalange that touches the virtual object can be calculated with a touching algorithm and a braking command can be given to the actuator. The GUI and haptic interface is shown in figure 12.

8. EVALUATION CONCEPT B

8.1 Kinematic Characteristics

The rotational resolution of the finger joints is lower than the design requirements. The used potentiometers have an accuracy of 0.5°. With the transfer ratio of the RLM, the resolution improves up to 0.12°. Figure 13 shows the range of the fingertip without and with the haptic interface. The range of the fingertip with haptic interface is limited because of the limited freedom of rotation of the PIP joint. Rearrangement of the design parameters or calibration of the angle scaling in the software for the PIP joint can overcome this limitation. This limitation is of no significance for practical use, because all tasks can be performed.

8.2 Dynamic Characteristics

The angular position, velocity and acceleration are measured of the MP1 joint. A flexion and extension movement of maximum amplitude and speed, possible with the exoskeleton, generates the input signal of the MP1 joint. The values are given as function of the time in figure 14. The graph shows that the flexion movement is faster than the extension movement. The speed difference is due to the natural incapability of the extension movement of the finger and the asymmetric force distribution of the finger.

8.3 Force Characteristics

The friction forces which are exerted perpendicular on the finger phalanges during free finger motion are smaller than 0.1 [N]. This value is in conformance with the design requirements. The brakes are capable of locking the circular links up to 50% MVC, which is sufficient for normal operation.

8.4 Braking Characteristics

A position error will occur, due to the braking time that is required to actuate the brake for locking the RLM. The joint angular velocity is around 5 [rad/sec] with normal grasping. The time required to brake the finger joint is below 10 [msec]. The corresponding position error is smaller than 1°. When the grasping speed increases the corresponding brake time and error increases. This can be compensated by using other actuators, which have faster response and can exert higher forces on the brake cable.

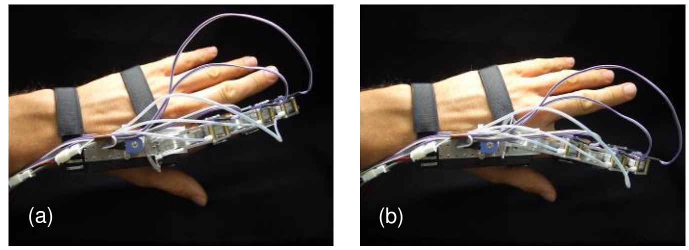


Figure 10: Top view of the concept B prototype: (a) full adduction, (b) full abduction.

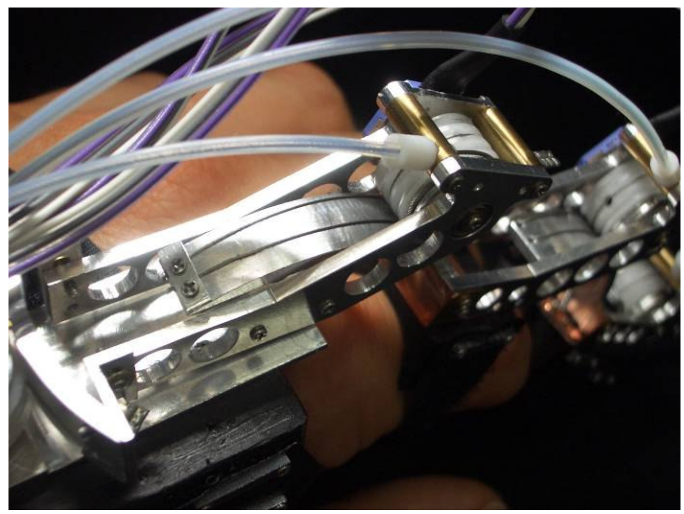


Figure 11: Concept B prototype, a close-up view of the RLM of the MP joint and complete exoskeleton.

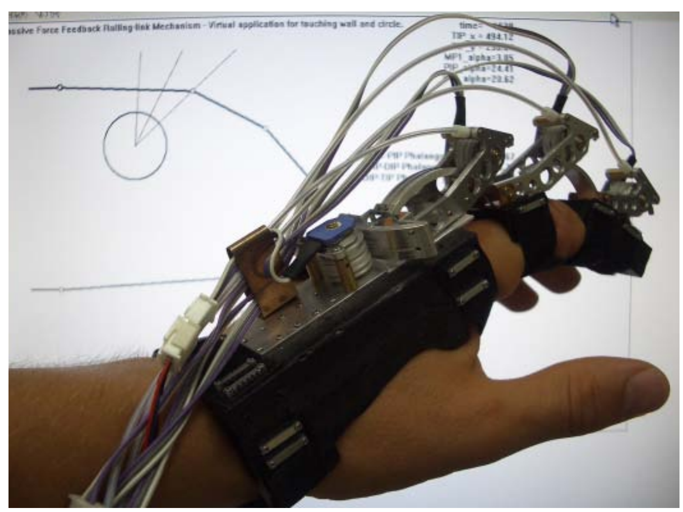


Figure 12: Concept B prototype, haptic interface with graphical user interface.

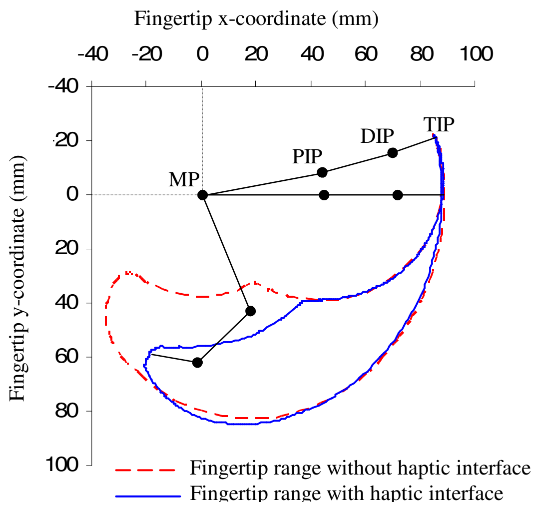


Figure 13: Range of motion of the fingertip, without and with haptic interface.

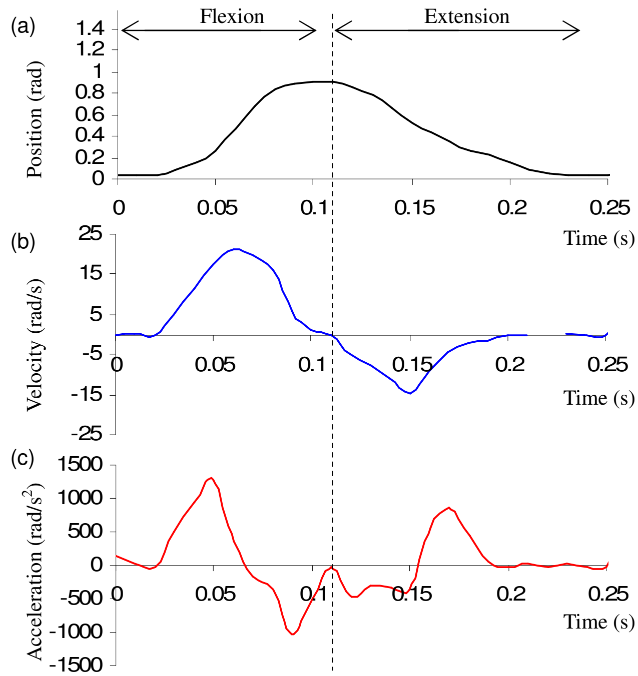


Figure 14: Graph as function of time of the MP1 joint: (a) angular position, (b) angular velocity, (c) angular acceleration.

8.5 Multi-Point Force Feedback Evaluation

With the developed master hand, there are two force feedback-grasping methods possible:

1. Force feedback of the finger when the fingertip encounters an object (single point force feedback).
2. Force feedback at every separate finger phalange when a finger phalange or fingertip encounters an object (multi-point passive force feedback).

Experiments with six subjects are executed to determine the effectiveness of proposed method 2. Subjects are asked to grasp a circle with their index finger with grasping method 1and 2. The subjects have the GUI as visual input. In Fig. 8b, the GUI with exoskeleton is shown. For both grasping methods the time to perform the grasping task, or grasping time, is measured. The average grasping time of the subjects for grasping method 1 is 6.8 [sec] with a standard deviation of 0.61. The average grasping time for grasping method 2 is 3.9 [sec] with a standard deviation of 0.42. Grasping method 1 allow that phalanges will enter the body of the virtual object. In reality, this will result in an unwanted movement of the object when the object can move freely in space. When the object is fixed, unwanted forces are exerted on the slave hand and object, which could result in damage. Grasping method 2 allows the phalanges to touch the object without entering the circle body. Therefore, faster and more stable grasping is established with grasping method 2. A comparable study of Koda and Maeno showed a similar result [19].

9. FUNCTIONALITY EVALUATION

In this paper, a general evaluation method is proposed to evaluate the functionality of a haptic interface that allow comparison between similar developed multi-point force feedback haptic interfaces in the future. Standardization of this evaluation would be desirable. The evaluation of the functionality of the developed master hand is carried out by an experimental setup as is shown in figures 15 and 16. The goal of this experiment is to measure the usability and reality of the force feedback of the master hand by detecting the shape of hard-contact objects. The time needed to recognize an object's shape, or recognition time t_r in [sec], is used to quantify the functionality of the haptic interface.

Six subjects have to recognize an object shape by touch without making use of visual input. Different object shapes and touching methods are used during the experiment. Firstly, two basic object shapes are used, which are a wall and cylinder. The wall is setup under a decreasing, horizontal and increasing slope, see table 4. The cylinder with a diameter of 20 [mm] is positioned at three positions, which are at the MP joint, PIP joint and DIP joint. The placement is respectively 30, 55 and 80 [mm] horizontally and 25 [mm] vertically from the MP joint. Secondly, there are several touching methods possible, dependent of active or passive force feedback. A haptic interface allows normal touching with active force feedback. With passive force feedback, the operator has to make a tapping movement to identify the object shape. With both methods, no tactile information is available. Therefore, four touching methods are proposed to evaluate the functionality of concept B with the multi-point passive force feedback principle:

A. Normal touching, this includes rubbing and tapping.
B. Tapping only.
C. Tapping only, with blocked tactile sensors. This is achieved by covering the touching surfaces of the

finger phalanges with thick plastic tape to mask the tactile sensory input for shape recognition.

D. With the passive force feedback haptic device.

This experimental setup consists of a frame to fix the position of the MP2 joint and a frame to fix the objects. The fixed hand with a real increasing slope as an object is shown in figure 15a. Figure 15b shows operator with the haptic interface when touching a virtual increasing slope. Figure 16a shows the operator with a cylinder nearby the MP joint, this object shape is simulated in figure 16b with the haptic interface.

All subjects got a learning period with to get used to the haptic interface the haptic interface of five minutes. The experiments are carried out in a random order. The results of the experiments are shown in table 4. This table shows a figure of the object shape. The touching method with the corresponding average recognition time and standard deviation is presented for every object shape.

The results show an increasing average recognition time when only tapping is allowed in comparison with normal touching, respectively method B and A. The recognition time increases further when the tactile sensors are mask, which is method C. Method C is most comparable with the object shape simulation with the haptic interface or method D. Method D takes on average twice as much time to recognize an object than method C. Method D takes more than three times the average recognition time of method A. In general, the results showed that passive force feedback has a limited functionality without visual feedback.

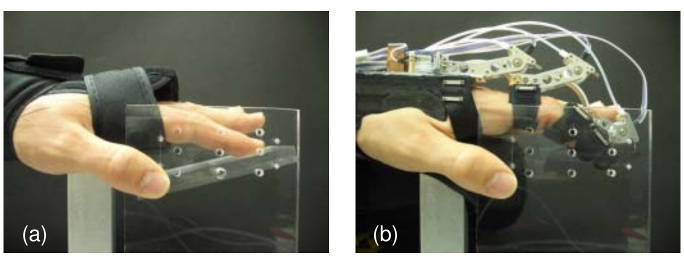


Figure 15: Side view of the functionality evaluation of concept B prototype: (a) real increasing slope, (b) virtual increasing slope.

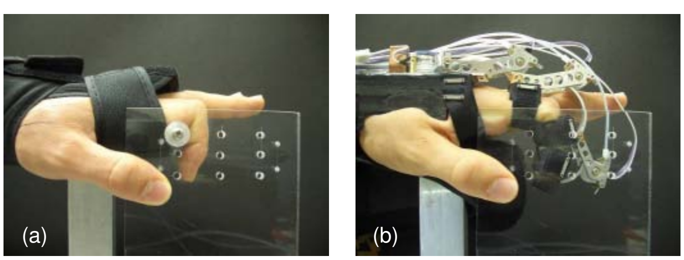
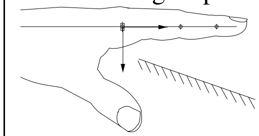
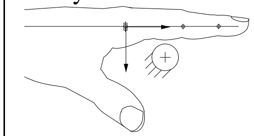
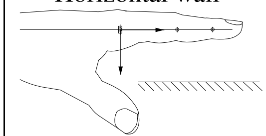
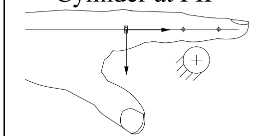
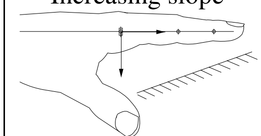
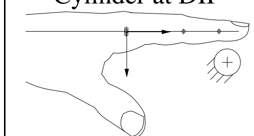


Figure 16: Side view of the functionality evaluation of concept B prototype: (a) real cylinder at MP joint, (b) virtual cylinder at MP joint.

Table 4: Results of the functionality experiments with the passive force feedback haptic interface of concept B.

	Decreasing slope				Cylinder at MP			
								
Method	A	B	C	D	A	B	C	D
Ave. t_r [s]	2.1	2.7	3.7	6.4	1.7	2.3	3.5	5.2
Stand. dev.	0.5	0.8	0.6	0.6	0.4	0.4	0.3	1.1
	Horizontal wall				Cylinder at PIP			
								
Method	A	B	C	D	A	B	C	D
Ave. t_r [s]	2.3	3.5	3.9	7.7	1.9	3.4	4.0	7.4
Stand. dev.	0.4	1.0	0.9	0.8	0.6	0.9	0.8	0.3
	Increasing slope				Cylinder at DIP			
								
Method	A	B	C	D	A	B	C	D
Ave. t_r [s]	2.0	3.3	4.3	8.0	1.9	2.4	3.6	6.5
Stand. dev.	0.3	0.7	0.9	1.3	0.3	1.0	0.4	1.1

10. CONCLUSIONS

In this design study, the systematic design approach of Pahl and Beitz resulted in two new concepts for a haptic interface for the index finger. Both concepts make use of a RLM per DOF. The RLM can exert a perpendicular force on the finger phalange and is a highly efficient mechanism. The angular position of the joints can be measured with high accuracy and simple kinematics. Concept A is a statically balanced haptic interface, which makes use of a RLM with an integrated constant torque spring per DOF for perpendicular and active force feedback. The flexible outer cable causes friction forces and more research has to be carried out to make this concept more viable. Concept B utilizes a mechanical tape brake at the RLM for passive force feedback. The concept has low weight, high backdrivability, high safety and is comfortable for the operator, although only hard-contact surfaces can be simulated. A proposal has been made for evaluating the functionality of multi-point force feedback haptic interfaces with passive or active force feedback. Experiments showed that the functionality of passive force feedback is limited.

11. FUTURE WORKS

The future works will be focused on the design and development of the thumb module to create a 20 DOF portable master hand. The mechanism and exoskeleton are further miniaturized to reduce weight and size. A future research field is the simulation of object stiffness by brake force adjustments. Research has to be carried out to implement actuators for active force feedback to improve the functionality. A combination of passive and active force feedback allow hard and soft contact simulation. Interesting developments for direct mounted actuators are the lightweight flexible electrostatic motors, which can be formed in circular shapes for the perpendicular force feedback.

Any mechanism will be redundant in the far future. This possibly can be accomplished by controlling the already available actuators, or muscles, inside the hand and upper arm.

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