The KIT Prosthetic Hand: Design and Control

Pascal Weiner*, Julia Starke*, Felix Hundhausen, Jonas Beil and Tamim Asfour

***Abstract*— The development and control of prosthetic hands is an active research area and recently progress in mechatronics, sensor integration and innovative control has been made. However, integration of different components into a prosthetic hand remains challenging due to space constraints, the requirements regarding holistic integration and the need for a user interface. In this paper, we present the KIT prosthetic hand, a novel five-finger 3D printed hand prosthesis, with its underactuated mechanism, sensors and embedded control system. The hand mechanics is based on the underactuated TUAT/Karlsruhe mechanism with two motors actuating 10 degrees of freedom. The mechanism has been realized in 3D printing technologies to facilitate a personalization of the prosthetic hand in terms of size and kinematic parameters. The prosthesis has been designed as a 50$^{\text{th}}$ percentile male hand. It integrates an advanced embedded system as well as an RGB camera in the base of the palm and a colour display in the back of the hand. Experiments indicate a finger tip force of $7.48\,\mathrm{N}$ to $11.82\,\mathrm{N}$, a hook grasp force of $120\,\mathrm{N}$ and a hand closing time of $\sim 1.3\,\mathrm{s}$.**

I. Introduction

Each year over 12.000 people in the European Union experience work accidents resulting in traumatic amputation [1]. Prostheses can make an important contribution to enable these people to regain autonomy in daily life. Traditional myoelectric prosthetic hands rely on the user for control. To grasp an object, a prosthesis user has to concentrate on the task of grasping for both positioning and orienting the prosthesis with respect to the object and selecting the appropriate grasp via the myoelectric interface. As user studies show, amputees wish to reduce the visual attention necessary during grasping [2], [3]. The limited bandwidth of the myoelectric interface as well as the fact that the quality of EMG signals differs significantly according to the electrode placement and user condition contribute further to a slow execution of grasping tasks. For that reason, sensors enabling environmental perception and high-level control algorithms are desirable as they further strengthen the reliability of the system while reducing the cognitive burden for the user. On that account, giving the user feedback is of great assistance by increasing the predictability of the prosthesis' behavior. However, the tight sizing constraints of a human-like hand and the need for energy efficient electronics additionally challenge the integration of appropriate mechatronics in terms of adaptive mechanisms, computing power, sensors and feedback systems into a prosthetic device.

*These authors contributed equally to the manuscript

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The authors are with the Institute for Anthropomatics and Robotics, Karlsruhe Institute of Technology, Karlsruhe, Germany {pascal.weiner, julia.starke, asfour}@kit.edu

Fig. 1: The KIT prosthetic hand. The underactuation mechanism allows the fingers to adapt to object's shape.

In this paper we present the first prototype of the KIT prosthetic hand (see Figure 1), with which we aim to approach the problem of the development of advanced personalized hand prostheses with the ability of semi-autonomous grasping to reduce the cognitive burden of the user. To this end, we rely on intelligent mechanisms allowing adaptation of the grasp to the object shape as well as the integration of additional sensing capabilities for scene perception. In terms of mechanical design an adaptive, under-actuated mechanism is used to allow the fingers to wrap around arbitrarily shaped objects. The sensor system includes position sensors in the two motors and an RGB camera for vision-based grasping. The on-board embedded system provides the possibility to integrate proprioceptive sensor information, visual information, user feedback and status information via Bluetooth. To the best of our knowledge the proposed hand prosthesis is the first device which integrates a camera in the palm. We consider the highly integrated realization of an affordable hand prosthesis with an adaptive mechanism and an advanced embedded system as the major contribution of our work.

The paper is structured as follows: In Section II we introduce the state of the art in prosthetic research. Section III describes the design of our hand prosthesis. We then present empirical results for various performance characteristics, grasping ability and the proposed vision system for semi-autonomous grasping in Section IV. Section V concludes the paper with a discussion and an outlook on future work.

II. Related Work

The design of actuation mechanisms for standalone prosthetic devices is very challenging in terms of space constraints and power consumption. Although the approach of individual joint actuation exists, its implementation [4] also proves the vast space requirements usually not available in hand prosthetics. A common means to deal with space limitations in prosthetics and robotics is the concept of underactuation, the joint actuation of several degrees of freedom by one motor. Several recently developed prostheses couple middle, ring and little finger via series elastic elements allowing a certain amount of shape adaptability, however, restricting the angular distance between the coupled fingers to some extent. The thumb and index finger are actuated individually [5], [6], [7]. The SSSA-MyHand comprises a Geneva Drive and four-bar-mechanism coupling, which allows to drive index finger flexion and thumb abduction with the same actuator, therefore reducing the total number of motors needed to three [8]. The Softhand Pro-D is carrying the concept of underactuation to a maximum by operating all fingers and the thumb with a single actuator [9].

In humanoid robotics, whippletree couplings like the TUAT/Karlsruhe mechanism are widely used to allow free movement of underactuated fingers irrespective of partial blocking ([10], [11]). Implementations of related mechanisms into a prosthetic hand have been presented by Belter and Dollar in [12] as well as Kamikawa and Maeno in [13] proving the general potential of the provided shape adaptivity. However, these works also demonstrate the significant challenges regarding the spatial integration of a comparable actuation unit into a standalone device.

In research a broad spectrum of different sensor modalities is used to facilitate more sophisticated, context-aware prosthetic control schemes. A detailed overview over sensors directly embedded in prosthetic hands is provided by Saudabayev and Varol [14]. For commercial purposes, Touch Bionics utilizes small Bluetooth tokens that can be associated with specific preshapes and gestures [15].

For prosthetic control, the sensor strategies to acquire proprioceptive information and the user's intention differ including inertial measurement units [16], [17], gaze tracking data [18], [19] and direct state estimation by the prosthetic device. However, all advanced control schemes rely on computer vision methods for environmental perception. These are comprised of sophisticated stereo vision [16] or depth camera systems [18] mounted in the experimental environment, augmented reality glasses [20] and webcams attached to the prosthesis [17], [21], [22], [23]. Especially the latter show promising results regarding the possibility of intelligently controlled standalone prosthetic devices offering grasping support without the need for a specially sensorized environment.

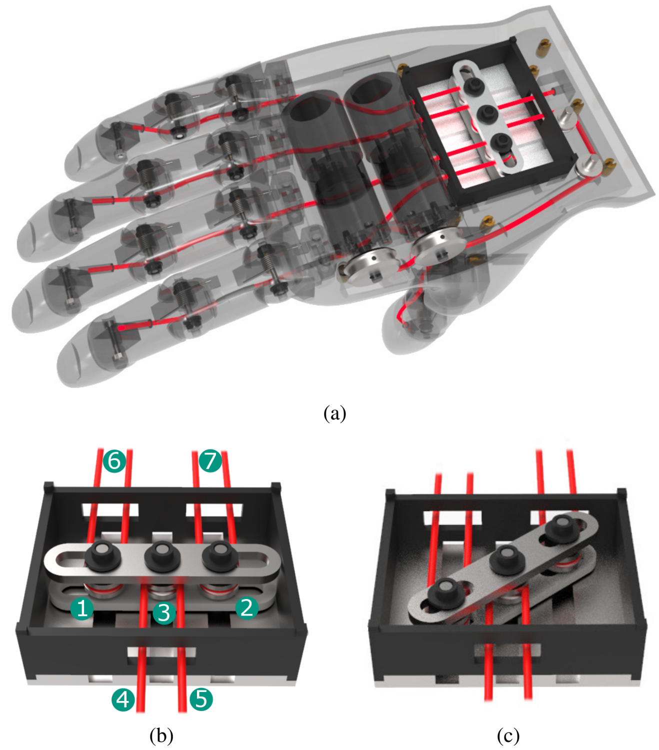


Fig. 2: Tendon routing within the prosthesis (Tendons and guiding tubes in red) (a) and the force distributing mechanism with all tendons pulled equally (b) and with the main rocker rotated caused by blocking the two rightmost fingers (c)

III. Design and mechatronics

First, we introduce the key requirements underlying the mechanical design and embedded system of the hand. We continue with a detailed explanation of the hardware of the prosthesis beginning with the underactuated mechanism and the general mechanical design. The section concludes by describing the integrated embedded system and camera.

A. Key Requirements

The development of our prosthesis is driven by several requirements concerning mechanics, embedded system and grasping capabilities. To ensure human-like appearance the complete hardware including motors, mechanisms, embedded system, sensors, user feedback and user interface shall be integrated into the palm of an average male hand. It should be fully actuatable and controllable as standalone unit without the need for any external computing resources.

To allow grasping of arbitrarily shaped objects, special attention should be paid to maximizing the possible angular distance between two fingers while providing sufficient force and closing speed to grasp and manipulate objects of daily living. The integration of user feedback is crucial for system transparency in myoelectric prostheses as the acceptance and trust regarding a semi-autonomous prosthetic device strongly depend on its behavior [24]. Feedback allows for intervention of the user avoiding the execution of malformed actions.

B. Mechanism

To achieve versatile grasping with the given power and space constraints, the prosthesis is designed as a mechanically underactuated system. All four fingers are simultaneously driven via a force-distributing transmission based on the TUAT/Karlsruhe mechanism [10], [11]. The thumb is actuated by a second motor. The structure of the mechanism allows the fingers to naturally shape around arbitrary objects. By these means, all fingers are closed until contact is achieved, irrespective of blocked movement in other joints.

Two fingers are connected with one single Dyneema tendon with a diameter of $0.4\,\mathrm{mm}$ respectively, running over freely movable deflection pulleys (indicated by 1, 2 in Figure 2) guided within a single rocker. This bar serves as the main rocker equally distributing the force between the two tendons driving the index and middle finger (6) and the ring and little finger (7) respectively. The force distribution between the two fingers is accomplished via the connecting tendon. As long as both fingers are moving freely, the deflection pulley is moved by the rocker equally shortening the tendon length in both fingers. If one finger is blocked by an object, the tendon winds around the pulley (1 or 2) allowing to further close the finger which is not yet blocked. In this manner we are able to realize the complete force distribution within a bounding box of $53 \times 43.5 \times 19\,\mathrm{mm}^3$. Because of the small width of $10\,\mathrm{mm}$ of the rocker itself, the length of the mechanism depends primarily on the desired change in tendon length. The linear guiding with sliding contact bearings of all rocking parts ensures a well defined tendon routing. Together with the aforementioned miniaturization it enables the achievement of a large scale of integration within the strict space constraints of the prosthetic palm. The total width of the mechanism depends on the maximally possible difference in finger closing angle. With the proposed size of $53\,\mathrm{mm}$ completely independent finger closing is possible allowing an angular difference of $90°$ in each joint between arbitrary fingers. This behavior is demonstrated in the attached video.

The whole mechanism is actuated via a deflection pulley within the rocker (3). The tendon is fixed at (5) and actuated via (4) by one of two identical DC-motors (2224U012SR, Faulhaber GmbH). The other motor performs direct thumb actuation. The motors are equipped with 86:1 transmission gearing (Faulhaber Series 20/1R) and incremental position encoders (Faulhaber IEH2-512).

C. Mechanical Design

The prosthesis has been designed to be the size of a 50^{th} percentile male hand according to the German standard specification (DIN 33402-2) in hand length, width and depth as shown in Table I. The basic mechanical structure of the prosthesis is depicted in Figure 3. The housing is manufactured by selective laser sintering out of PA2200. This rapid prototyping technique is chosen to allow for a personalized production process offering a smooth scalability of the prosthesis according to the user's need. Four functional mechanical parts within the mechanism are machined from high-strength aluminium.

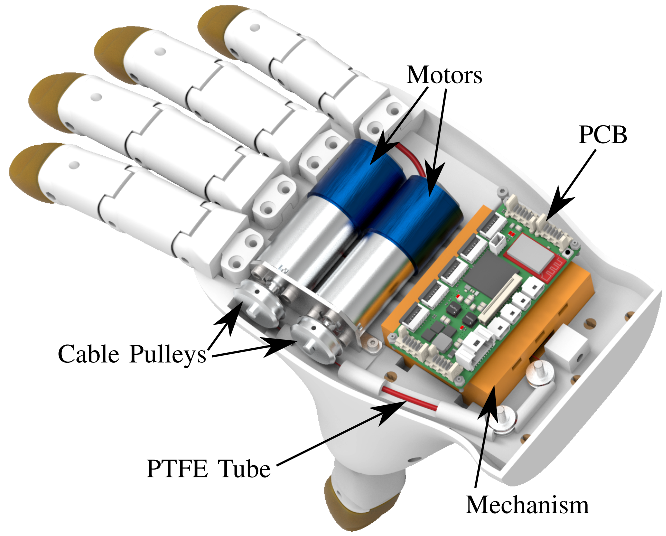


Fig. 3: The components integrated inside the prosthesis palm: motors, embedded system and underactuated mechanism

TABLE I: DIMENSIONS OF THE KIT PROSTHETIC HAND

Hand Part		Size (mm)
Palm	Length	111
	Width	87
	Depth	30
Thumb	Proximal Phalanx	37
	Distal Phalanx	37.7
Index Finger	Proximal Phalanx	29.9
	Intermediate Phalanx	28
	Distal Phalanx	27.1
Middle Finger	Proximal Phalanx	33.6
	Intermediate Phalanx	32.3
	Distal Phalanx	28
Ring Finger	Proximal Phalanx	30.1
	Intermediate Phalanx	31.3
	Distal Phalanx	28.6
Little Finger	Proximal Phalanx	22.8
	Intermediate Phalanx	23.9
	Distal Phalanx	27.3

As only the absolute lengths of the whole finger are defined by the standard mentioned above, the relative partitions of the individual finger segment lengths are inspired by the human hand reference model of the Master Motor Map as described in [25] and expanded according to recent studies [26]. Since the parametric finger design allows independent scaling of all phalanges between the 5^{th} and 95^{th} percentile male finger lengths, the chosen measures are exemplary and can be easily adjusted to fit the user's able hand.

While proximal and intermediate phalanges of the fingers are manufactured from PA2200 matching the strength and visual appearance of the palm, the more flexible material PEBA2301 is chosen for the distal phalanges. The grasping capability especially on smooth object surfaces becomes less dependent on the applied force because of the surface

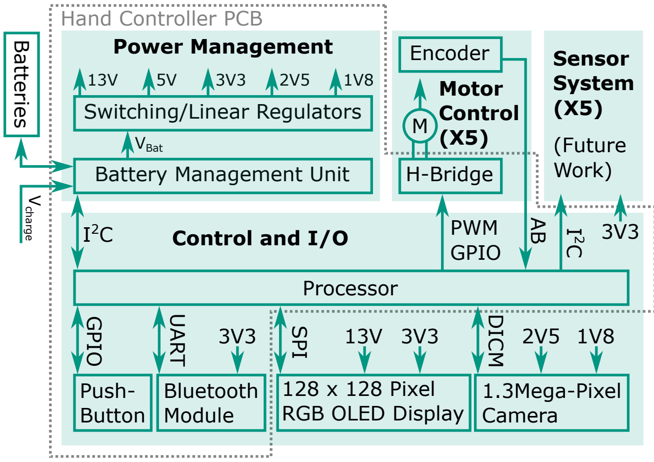


Fig. 4: Architecture of the developed embedded system

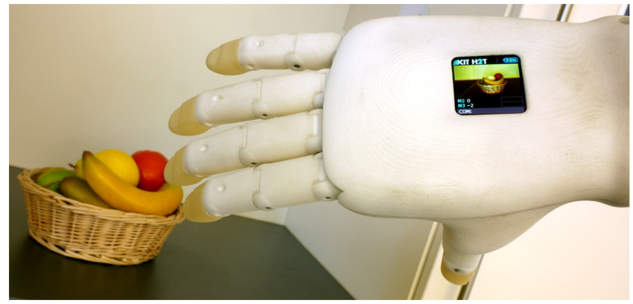


Fig. 5: Display mounted in the backside of the hand

compliance and higher friction of this material. This leads to higher grasp stability.

The tendons pass through PTFE tubes inserted into the 3D-printed material in order to reduce friction. Additionally all active joints and deflection pulleys include ball bearings. Custom made springs in every joint ensure the passive reopening of the fingers. By defining a higher pretension in the distal joints, we strive for a human-like closing order of the finger segments with the proximal joints closing earlier.

The material cost for all hand parts amounts to about 1000 € with the biggest expense factor being the two geared motors with 474 €.

D. Vision and Embedded System

An embedded system was developed to enable self-contained control of the prosthesis. The goal of the development is to provide sufficient computing power for control and visual tasks while keeping the energy consumption at a minimum. The embedded system is designed to be directly connected to four Lithium-Ion batteries with a total voltage between approximately $12\,\mathrm{V}$ and $16.2\,\mathrm{V}$. The batteries are charged and discharged through an integrated battery management system supporting USB Type-C power delivery for charging.

The control algorithms of the prosthesis are realized on an ARM Cortex M7 processor (STM32F7 series, STMicroelectronics) which includes amongst other things a parallel camera interface, diverse peripheral serial interfaces and various power saving modes. The processor operates at $216\,\mathrm{MHz}$. An overview of the embedded system architecture is given in Figure 4.

To take future extensions of the prosthesis, such as independent finger movements, into account, the embedded system includes five motor drivers, two of which are used in the current prosthesis, each capable of delivering $2\,\mathrm{A}$ and able to provide current measurement using a shunt resistor. Five connectors for I^{2}C interfaces and power supply are included to allow the connection of additional sensors in fingers and the thumb. The embedded system supports the Bluetooth Low Energy standard for communication with handheld devices such as smartphones or wearables. In total the hand controller PCB has a size of $63\,\mathrm{mm} \times 30\,\mathrm{mm}$. The embedded system is further connected to an OLED colour display located at the back of the hand (see Figure 5). This is used to provide system feedback like a battery indicator or status information for semi-autonomous functions.Inspired by the promising results of [17], [21], [22], [23], an 1.3 megapixel RGB camera is located at the base of the thumb on the palmar side of the hand. Similar to the mechanical personalization, camera and display can be selected according to the user's needs.

IV. Experiments and Performance Evaluation

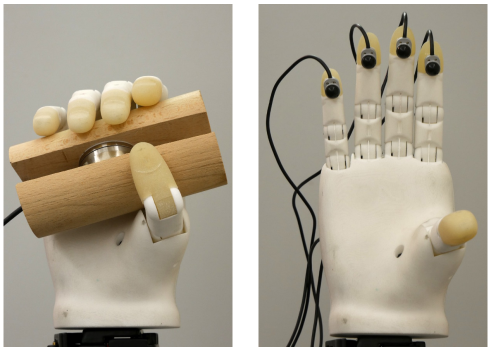
We provide experimental results for various key parameters of the prosthesis. This includes dynamic characteristics like fingertip forces, joint angle velocities and hand closing speed as well as power consumption. In addition, we provide results concerning the quantification of hand grasping ability and preliminary vision based object recognition.

A. Grasping Forces

The force applied in a hook grasp was measured by grasping a cylinder of $31\,\mathrm{mm}$ diameter fixed at a calibrated hanging scale and incrementally increasing the pulling force applied at the prosthesis wrist until the fingers are unclenched. This way, a hook grasping force of $120\,\mathrm{N}$ was achieved with the reason of failure being a ripped tendon in the actuation mechanism. With all important mechanical parts still intact, a higher hook grasping force can be expected by integrating stronger tendons.

To assess power grip force, a wooden cylinder with $49\,\mathrm{mm}$ diameter was longitudinally divided and a calibrated 6 DoF force/torque sensor (Mini 40, ATI Industrial Automation) was mounted between both wood pieces, as shown in Figure 6a. The resulting test object was grasped in a horizontal and vertical hand orientation. Both experiments were repeated ten times. The power grasp force measured with the indicated cylindrical test object yielded $24.19 \pm 1.91\,\mathrm{N}$.

For simultaneous measurement of the finger tip forces we used a combination of four calibrated Optoforce sensors (OMD-10-SE-10N, Optoforce Ltd.), which were attached to the distal phalanges of the fingers as shown in Figure 6b. Figure 7 shows the mean values of the finger tip forces obtained while grasping a block of $60\,\mathrm{mm}$ height within ten repetitions. Index and middle finger directly oppose the



(a) (b)

Fig. 6: Experimental setup to measure the power grip force (a) and the maximum finger forces (b)

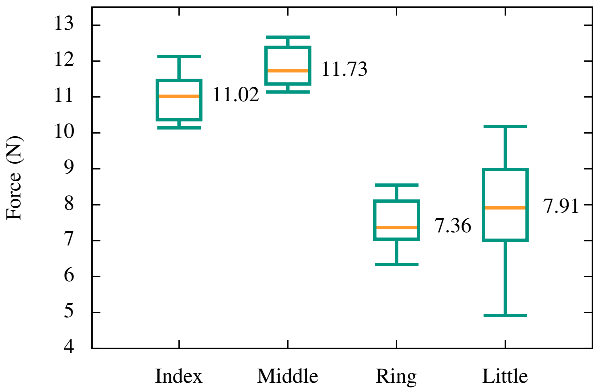


Fig. 7: Triangulated finger tip forces; with the mean value depicted in orange, the upper and lower box boundaries being the first and third quartile and the outer lines denoting the extrema

thumb and hence exert the major part of the force applied to the object, while ring finger and little finger stabilize it. The measured finger tip forces of $7.48\,\mathrm{N}$ to $11.82\,\mathrm{N}$ are in the range of commercially available prostheses [12].

B. Finger Flexion Behavior

To asses the finger flexion speed and trajectory, a passive marker based optical tracking system (VICON MX system with 10 T10 and 4 Vero cameras, $100\,\mathrm{Hz}$, VICON Motion Systems Ltd.) was used. For the recordings each individual finger phalanx as well as the palm were equipped with optical markers. During the recordings, the hand was closed and 3D-trajectories for each marker were captured.

The hand closing speed was calculated with a mean of $1.32\,\mathrm{s}$ and a standard derivation of $42\,\mathrm{ms}$. The measured joint angle velocities of proximal and distal finger joints are listed in Table II. The effect of different spring pretensions as described in Section III-C is visible in the distinct closing speeds of the proximal and distal joints. Furthermore the proximal joint begins to close in advance of the distal joint. By these means a human-like finger tip trajectory as described by Kamper et al. [27] is achieved. This is shown

TABLE II: MEASURED FINGER JOINT ANGLE VELOCITIES FOR PROXIMAL AND DISTAL FINGER JOINTS BASED ON DATA COLLECTED FROM TEN TRIALS

	Proximal (deg/s)		Distal (deg/s)	
Finger	Mean	Derivation	Mean	Derivation
Index	120.92	3.69	91.07	1.48
Middle	120.24	1.80	66.2	1.29
Ring	100.88	2.06	69.77	1.46
Little	94.81	3.24	66.72	2.50

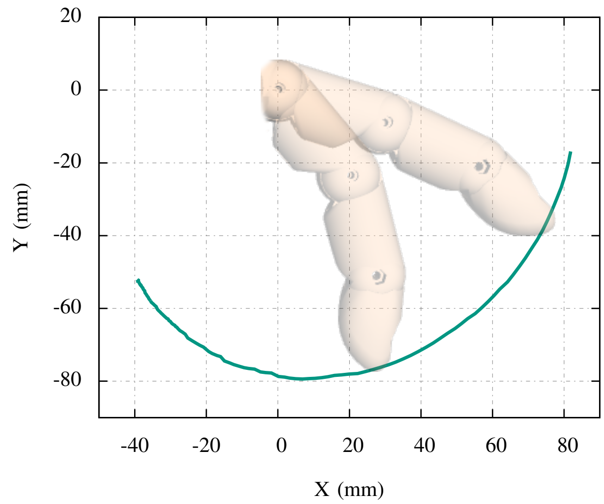


Fig. 8: Index finger trajectory

exemplary for the finger closing trajectory of the index finger in Figure 8.

C. Energy Consumption

To quantify the power consumption, the current draw and supply voltage were measured in idle mode, with the camera and vision processing active as well as during grasps (all systems active). A Fluke 79III Multimeter (Fluke Corporation) was used and connected to the prosthesis in a current error circuit. A power of $154\,\mathrm{mW}$ is drawn in idle mode, meaning a deactivation of the vision and feedback system and the motor driver unit but with the processor fully active. During vision processing the described components are activated causing a power consumption of $\sim 1.2\,\mathrm{W}$, depending on the image shown on the display. During grasping actions up to $20.4\,\mathrm{W}$ are needed, depending on the selected grasp force.

D. Grasping Ability

To quantify the grasping ability of the prosthetic hand, a study is conducted including four categories of the YCB object set. We conduct an adapted form of the Gripper Assessment Protocol proposed by Calli et al. [28]. Due to the different focus of interest in hand prosthetics, two changes are applied to the mentioned protocol. The objects' position is not considered, as the prosthesis user directly controls the free space motion, making it independent from

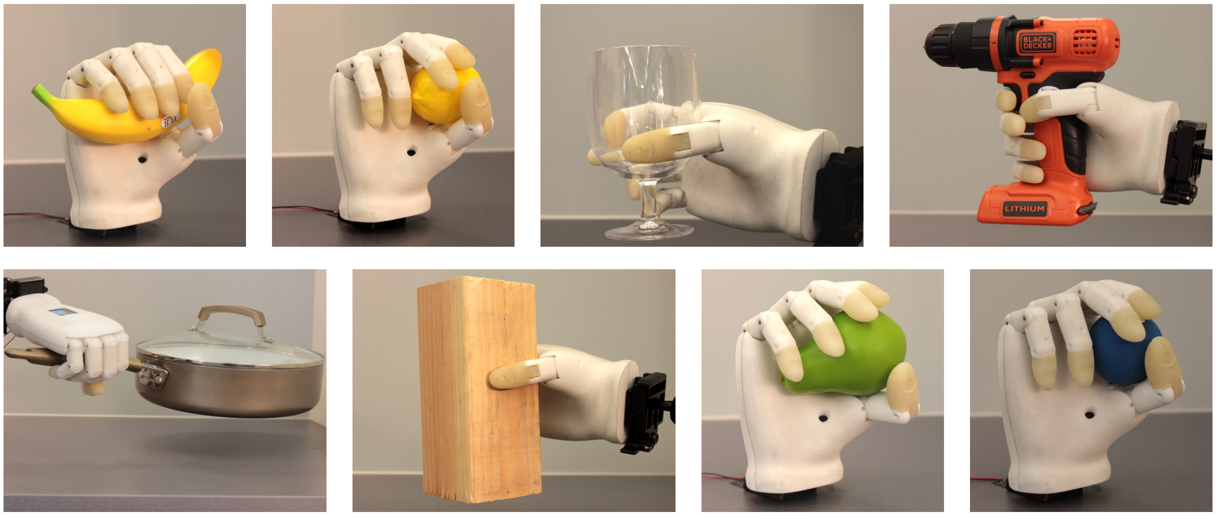


Fig. 9: The KIT UPro Hand grasping several objects

the investigated hand. Further the complete object set except for the task items is tested, as the original protocol mainly focuses on workshop items whereas a prosthetic hand is used in all activities of daily living also including household and kitchen environments.

Our control allows hand preshaping in terms of hand aperture and independent timing of thumb and finger closure. By these means, 85.2% of the remaining 60 objects can be grasped successfully from a flat surface, scoring 193 of the total 230 points. Figure 9 presents several examples of successfully performed grasps. Failed grasps mainly occurred when trying to lift very thin objects like the credit card or small ironmongery. A correlation between the shortest side of the object and its graspability is noticeable with Goodman and Kruskal's Gamma yielding 0.85.

E. Preliminary Vision-based Object Recognition

For object classification and grasp control we implemented an embedded vision system that can distinguish between a set of six kitchen objects and decide on preshape aperture and grip force based on exmaples stored in a database. For that purpose, a 128x72 Pixel image is captured by the in-hand camera and is evaluated by a convolutional neural network (CNN) running on-board the embedded system.

The training set consists of 300 images of each object captured with the embedded camera in different household environments. The pretrained weights of the obtained network are implemented within the embedded system's flash memory. The size of the CNN allows inference in 371 ms.

With a test set of 50 images per object a recognition accuracy of 97 % is achieved. Figure 10 shows screenshots of the embedded display during the execution of this experiment. This demonstration is a first proof of concept towards an embedded object classification for semi-autonomous grasp selection and preshaping. To keep the size and memory requirements of the neural networks small, we aim for several

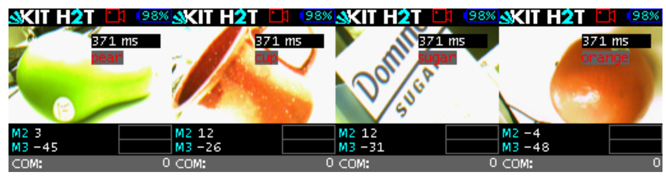


Fig. 10: Screenshots from the embedded hand display during the vision experiments.

context dependent CNNs. Based on the user's environment (e. g. kitchen, office, ...), the corresponding network can be selected. The user could parametrise preshapes for new objects and e. g. execute the object recognition task on her smartphone using the Bluetooth interface.

V. Conclusion

This paper presents a novel underactuated, sensorized hand prosthesis, combining a compliant, shape adaptive actuation mechanism, an in-hand vision system and the means for extensive user feedback via a colour display. We integrate the complete actuation and the embedded system into a naturally sized housing manufactured in an adaptable, low-cost rapid prototyping. The prosthesis is sized according to a 50^{th} percentile male hand. The hardware design can be seen as a blueprint. It allows for personalization in hand scaling and technical equipment. An anthropomorphic fingertip movement trajectory is achieved. The high-performance embedded system allows real time environmental perception using the in-hand camera. The power grasp force of 24 N and a hand closing time of ~ 1.3 s are sufficient to perform everyday activities.

We believe that the merit of the local intelligence available through the proposed perceptive capabilities of the device is also easily applicable to less underactuated prosthetic hands requiring an even more sophisticated control.

Despite the high degree of integration in mechanics and embedded system, our approach is limited in the amount of sensorization restricting the application of sophisticated control schemes as proposed with external sensor settings. Notwithstanding we see the integration of a more thorough multi-modal sensor system as well as its use in semi-autonomous control schemes as a promising future research topic. Based on the developed embedded system we therefore plan to extend our work towards a stand-alone prosthesis offering the amount of intelligent grasping support possible with the integrated computing power.

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