The KIT Robotic Hands – A Scalable Humanoid Hand Platform With Multi-Modal Sensing and In-Hand Embedded Processing

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***Abstract*— Humanoid robotic hands need to be versatile and capable of providing environmental information in order to serve as a platform for intelligent grasp control. To facilitate the design process of such hands, we present the KIT Robotic Hands. They have been designed to meet diverse application requirements through their scalability in size, actuation, sensorization and computing resources. The hands integrate a multi-modal sensor system, in-hand embedded processing capabilities, an adaptive underactuated mechanism and a continuously controllable thumb rotation to enhance dexterity. The flexibility of the design is demonstrated through two application-specific hand implementations: one is the ARMAR-7 hand, which has human hand dimensions for grasping daily objects in household tasks, the other is the ARMAR-DE hand, a larger hand designed for grasping bigger objects in decontamination tasks. We describe the design and mechatronics of the hands as well as an evaluation of the grasp success and image segmentation based on in-hand integrated camera and onboard processing of visual data.**

Fig. 1. The KIT Robotic Hand in a household scenario (ARMAR-7, bottom) and a decontamination scenario (ARMAR-DE, top)

I. Introduction and Problem Statement

To interact with the world around them, robots need robust hands to grasp and manipulate objects. To deal with objects usually manipulated by humans, a humanoid hand shape and kinematics are beneficial. Throughout recent decades, research on humanoid hand development has advanced significantly, mainly using the concepts of softness and adaptive actuation, as discussed in the survey by Piazza et al. [1]. Yet, humanoid robotic hands still lack the versatility, dexterity and sensing capabilities needed for dexterous grasping and complex manipulation. To overcome the current limitations we need i) dexterous hand kinematics, ii) efficient mechatronics in terms of space and complexity, iii) multi-modal sensing and iv) on-board processing capabilities. The hand kinematics need to provide all *degrees of freedom* (DoF) necessary to implement a wide range of different grasp types to tackle everyday tasks. The space within a humanoid hand is limited and therefore, simple yet efficient hardware design is needed.

In order to implement autonomous and reactive grasp control, multi-modal sensor data is needed for closed-loop control. Finally, local processing of multi-modal sensor data requires in-hand embedded computing resources. A comprehensive sensor system produces a considerable amount of data (e. g. a small camera alone has a data stream of more than 50 MBits/s). Since communication bandwidth with the main robot control hardware is limited, the hand itself needs to be equipped with processing resources. Thereby sensor preprocessing and close low-level control loops can be executed locally.

While hand designs exhibit significant advancements regarding hand kinematics, shape and size, few are equipped with sensors and capable processing systems. Most hands that tackle sensorization focus on one specific modality, most frequently tactile sensing. However, a flexible control for real-world scenarios greatly benefits comprehensive information on the scene and the status of the grasp execution. This may include information like the distance to objects, normal and shear forces, contact surface, vibration and slip, heat conduction and friction. We furthermore believe that it is beneficial to have computing resources available directly on the robotic hand. This allows for the quick preprocessing of high-bandwidth sensor data and the performance of low-level grasp control without the bottleneck of the robot-wide communication system. In addition, hands are often designed for a specific robot or application area. While inspiration can

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certainly be drawn from existing hand designs, the design engineering needs to be completely redone for every hand.

In this paper we present the design of the KIT Robotic Hands, a novel adaptable hand platform for the design of humanoid robotic hands scaled and tailored to the requirements of different robots and application areas. The hand design is scalable and can be adapted easily in terms of degrees of actuation, processing system and sensor setup to different scenarios . We provide a multi-modal sensor system including vision, depth, orientation and pose measurement, that provides a basis for versatile autonomous grasp control. The hands have an adaptively underactuated finger mechanism and a continuous, sensorized thumb rotation. This allows them to adopt a wide range of different grasp postures and adjust to various objects with low control effort. Further, we integrate an adaptable powerful processing system with a hybrid FPGA-microcontroller structure. By these means vision postprocessing and neural networks can be run directly within the robotic hand. The hand platform provides a general hand concept for a wide variety of applications. Within this paper we show two exemplary hands developed from this platform for assistive household tasks and decontamination tasks in hazardous environments, as shown in Figure 1.

II. Related Work

Since four decades scientists have been working on the development of humanoid robotic hands to replicate human grasp functionalities. Piazza et al. [1] give a comprehensive overview of the robotic and prosthetic hands developed during this period of time. The complexity and versatility of the human hand pose a major design challenge for human-inspired robotic hands. The actuation of the numerous hand joints and proprioceptive and exteroceptive sensing capabilities need to be realized within the strictly limited design space of a human-sized hand. To this end, the concepts of underactuation and soft kinematics are widely applied in order to achieve high adaptability and versatility in grasping while limiting the resources needed for actuation.

Adaptive underactuation couples several DoF to drive them with a single *degree of actuation* (DoA) while still allowing passive adaptation of the coupled joints. Due to the complex kinematics of the human hand with 21 DoF, many anthropomorphic robotic hands leverage this concept to reduce the number of required motors. To this end, either coupling the joints within one finger (e. g., [2], [3], [4], [5], [6]) or combined actuation of several fingers are applied (e. g., [7], [8], [9], [10], [11], [12]). Soft hands promote passive shape adaptation during grasping with flexible joint structures (e. g., [13], [14], [11], [12]) or continuous kinematics without specific joint locations ([15], [16], [17], [18]). Finger and grasp forces often range between 6 N and 10 N (e. g., [17], [19], [4], [20], [6]), but few specific hands can achieve significantly higher forces [5].

Most robotic hands rely on control hardware located outside of the hand itself. Only very few hands integrate an embedded system that goes beyond the basic motor driver hardware directly into the hand [5], [21]. Outsourcing hand control hardware is a reasonable approach for a fixed robotic arm that can be controlled by a workstation computer located next to the robot. For mobile systems however, the computational hardware needs to be fully integrated into the robot itself. Especially in humanoid robots , a slender, human-like appearance is of utmost importance and the design space is limited throughout the entire body of the robot. Therefore, it is highly desirable to perform basic sensor processing and motor control directly within the hand and reserve the central computation unit for high-level control. In addition, the local computation of low-level control and preprocessing reduces the requirements on bandwidth and performance of the robot communication system. This is particularly important for time-critical control tasks and data-intensive sensing modalities, especially vision.

Most robotic hands have some means of positional sensing, either by direct joint angle measurement ([22], [23], [4], [24]) or indirectly through motor encoders ([10], [19], [20], [12], [25]). Further sensorization of robotic hands is sparse and is mainly restricted to tactile sensing ([11], [21], [20], [12], [6], [25]). Research with industrial robotic grippers shows the merit of a diverse and multimodal sensorization of robotic endeffectors. Such in-hand-sensing complements the scene perception from global or head-mounted cameras and helps to overcome inaccuracies in the estimation of robot kinematics and object characteristics ([26], [27], [28], [29], [30]). Eye-in-hand setups using cameras [27], [28] or distance sensors ([29], [31], [30]) improve scene perception under occlusion caused by the approaching hand. They are especially beneficial in dynamic settings where distant fixed or head-mounted sensors have a high measurement uncertainty.

This paper presents a series of anthropomorphic robotic hands that share the same design principles, but can be scaled and customized to suit a wide range of robot designs and application areas. The hands integrate a multimodal sensor system including in-hand vision, distance, orientation and position sensing. In that way, they provide local proprioception and scene information for adaptive and dynamic grasp control. All actuation and the processing system are integrated directly in the hand. Thereby, complex grasp control can be performed directly on the hand without the need for any external computation or high-bandwidth communication. The humanoid hand kinematics are fully scalable in size and the actuation, processing and sensor setup are modular and can be adapted to the requirements of a specific robot.

III. Requirements

A robotic hand needs to be robust, strong and exceptionally flexible in order to provide comprehensive grasp and manipulation capabilities. This can be achieved by implementing a wide range of motion within five fingers with multiple joints per finger, thereby adopting a humanoid hand shape. This allows for a flexible adaptation to different tasks and objects and the control of joint stiffness and grasp type. If all DoF are actuated individually, the complexity of these versatile kinematics needs to be handled in robot control. To simplify control effort and mechatronic design, it is desirable to adaptively couple various DoF of the hand into a single DoA without sacrificing the adaptability among those joints. Therefore, an actuator concept based on adaptive underactuation is chosen to achieve simple, yet flexible grasp control.

Further, the hand shall provide a multi-modal sensor setup. Depending on the task and robot, the in-hand sensing needs to provide hand state information and local scene information to enhance and correct the robot's main perception. To this end, the hand shall allow for endeffector motion tracking and correction, reactive grasping using an eye-in-hand approach as well as depth-based object modeling and grasp planning. To achieve this, the hand needs to be able to acquire vision, distance, orientation and acceleration data directly onboard. In turn, the hand also needs local computational resources to preprocess sensor data and perform time-critical computations without the bottleneck of the robot-wide communication system.

Finally, the force, size and appearance of the hand need to be suited for the setting the robot shall operate in. Since the maximum grasp force is directly correlated to the actuator dimensions, the force and space requirements are not fixed. Rather, they are represented by a Pareto front with different optimal pairings for different applications. For example an assistive household robot needs average human-sized hands (not larger than the 50^{th} percentile male hand) and needs enough grasp force to lift daily objects (up to $1250\,\mathrm{g}$ [32]).Whereas a collaborative robot manipulating industrial components should have a hand that is $30\,\%$ larger than the human model and needs a higher grasp force to manipulate heavy structural objects (up to $5\,\mathrm{kg}$).

IV. Hand Design

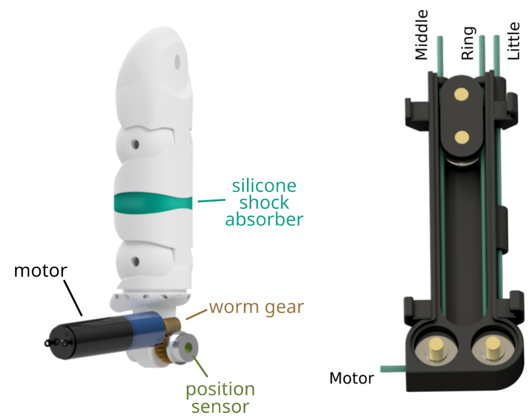
The modular design of the KIT Robotic Hands comprises the actuation of the hand, the mechanical design and the adaptable sensor system. All components will be described below. An adaptive underactuation mechanism allows for simple hand control while supporting different power and precision grasp types. The mechanical design is scalable including the actuation, that can be adapted based on specific requirements using an expert system. The multi-modal sensor system provides comprehensive data for grasp and manipulation control that can be processed directly on the powerful embedded system included into the robotic hand. The sensor setup is modular and can be adapted according to the application area and the size and cost requirements of the robotic hand. The modular design is described along two exemplary hands shown in Figure 1: one hand for grasping daily objects in household tasks, the ARMAR-7 hand, and another hand for grasping large objects in decontamination tasks, the ARMAR-DE hand.

A. *Actuation and Adaptive Mechanism*

The KIT Robotic Hands are driven by four motors actuating eleven DoF. In order to allow for precision pinch grasps, the flexion and extension of the thumb and index finger are each driven by an individual motor. A third motor actuates the flexion and extension of the middle, ring and little finger together via an adaptively underactuated mechanism integrated into the palm. The thumb rotation is driven by a fourth motor. The characteristics of all four motors are detailed in Table I for both hands. In comparison to the KIT Prosthetic Hands [33], two additional motors for thumb rotation and individual index finger flexion have been added.

TABLE I
Motor specifications for the ARMAR-7 hand and the ARMAR-DE hand

	Finger	Motor	Gearbox	Pulley D
ARMAR-7	Thumb Flex	2224U012SR	20 1/R 23:1	5 mm
	Index	2224U012SR	20 1/R 23:1	5 mm
	Fingers	2224U012SR	20 1/R 23:1	8 mm
	Thumb Rot	1024K012SR	10/1 16:1	–
ARMAR-DE	Thumb Flex	2232U024SR	22/7 43:1	7 mm
	Index	2232U024SR	22/7 43:1	7 mm
	Fingers	2232U024SR	20 1/R 23:1	12 mm
	Thumb Rot	1331T024SR	13A 16:1	–



(a) (b)

Fig. 2. Actuation of the thumb rotation (a) and adaptively underactuated mechanism driving the middle, ring and little finger (b)

The rotational axis of the thumb base is orthogonally placed to the thumb's flexion and is rotated towards the fingers by $15°$. The thumb actuation is detailed in Figure 2 (a). Since the thumb rotation moves perpendicular to the finger closing direction, the thumb opposition does not contribute to the grasp force. Consequently, the actuation is dimensioned significantly smaller than the three flexion motors. The thumb opposition axis is equipped with a hall-effect position sensor which allows precise measurement and control of the thumb's angle continuously between $0°$ and $90°$. Thumb opposition is actuated by a non-backdriveable worm gear. By these means, the thumb orientation remains fixed despite the contact forces within a grasp and does not require continuous control while holding an object. In order to protect the stiff worm gear mechanism from excess force peaks and absorb shocks exerted on the thumb, a layer of silicone is integrated into the proximal thumb phalanx.

The flexion of thumb and index finger is directly driven by individual motors. The middle, ring and little fingers are

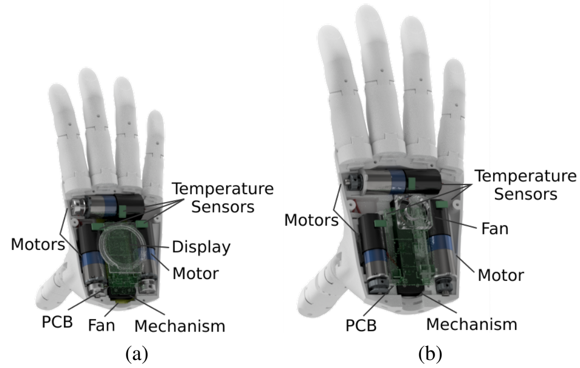


Fig. 3. Mechatronic components of the ARMAR-7 hand (a) and ARMAR-DE hand (b), both hands are depicted at the same scale

all connected to a single motor using an adaptively under-actuated mechanism. The mechanism is shown in Figure 2 (b) and was first presented by Hundhausen et al. [14]. It is an adaptation of the KIT Prosthetic Hand mechanism [33] and originally the TUAT/Karlsruhe mechanism [7]. Different from these earlier mechanisms, the thumb and index finger are actuated individually, allowing for pinch grasps. A tendon pulled by the motor drives the slider connected to middle and ring fingers. Both fingers are driven by a single tendon, that rotates around a pulley within the mechanism slider. The motor tendon is routed through the second pulley of the mechanism slider and then connects to the little finger. By these means, the force is evenly distributed among all three fingers with the full motor torque being applied to each finger. If one or several fingers are blocked, the other fingers can still continue to close. If the middle or ring finger is blocked, the tendon connecting both fingers rotates around the slider pulley. If both of them are blocked, the slider stops moving and the motor tendon can still pull the little finger. If, in turn, the little finger is blocked, the slider connecting middle and ring finger is pulled further down, continuing to close these fingers. By these means, the fingers can wrap around arbitrarily shaped objects without any need for software control.

B. Mechanical Design

The actuation is embedded into the palm of the hand together with the multi-modal sensors and the embedded system. An overview of the mechanical design of both hands including all mechatronic components is shown in Figure 3. A miniature fan provides active cooling to the densely packed computation and actuation hardware within the palm. The processing system and the flexion motors are equipped with temperature sensors to monitor the hand temperature and prevent overheating.

The fingers' proximal and intermediate joints are actuated with a range of $90°$. The distal joints are fixed at $20°$. The finger flexion is actuated via Dyneema tendons with a diameter of $0.4\,\mathrm{mm}$ in the fingers and $0.6\,\mathrm{mm}$ in the thumb. All joints are equipped with ball bearings and the tendon is routed through teflon (PTFE) tubes to minimize friction. Extension is performed passively by leaf springs located in the finger joints. In order to endure the small bending radius in the finger joints while exerting enough force to fully extend the fingers, stacks of three to five thin layers of spring steel are used. Due to the different joint diameter and finger weight, we use a $0.09\,\mathrm{mm}$ stainless steel (1.1274) for the ARMAR-DE hand and a $0.07\,\mathrm{mm}$ chromium-nickel steel (1.4310) for the ARMAR-7 hand. By adapting the number and material of the leaf springs, the stiffness of each finger joint can be adjusted individually. By these means, the spring stiffness is designed to be higher in the distal joints to ensure a human-like finger closing trajectory.

The fingers and palm housing are laser sintered from polyamide (PA1100). Pads on all fingertips and the inner palm surface enhance friction during grasping. The pads are made from silicone (Shore A 30) and are cast directly into the plastic parts. An optional display can be included in the back of the hand. It can be beneficial for various purposes, including debugging during hand control development, visualization of camera and other sensor data or conveying information in the interaction with humans. The display has been included in the ARMAR-7 hand, since this robot shall collaborate closely with humans.

C. Adaptable Hand Platform

From a mechanical point of view the main goal of the configurable platform is scalability. The design has to be adaptable to cover different hand sizes from small, human-sized hands for a robot interacting with humans to over-sized hands for a larger robot for industrial environments. Adopting human proportions results in a tight design space, in particular in the palm where the four motor-gearbox combinations, the embedded system and the underactuated mechanism are located. This limits the maximum size and thereby also power of the motor-gearbox actuation systems. As a consequence, scalability does not only have to take the proportions but also the motor-gear-box selection into account.

To implement scalability, two main tools are used: a parametrized CAD model and an expert system [34] that supports the motor-gearbox selection for prosthetic and robotic hands [35]. The expert system incorporates all knowledge from our previous hand designs in an ontological knowledge base. It is comprised of a large database of catalog components as well as rules linking the requirements and catalog components to actual hand specifications. The expert system supports the dimensioning of the functional mechatronic components based on the size and performance requirements for a specific application. For the presented hands the main goal was a maximum force while being able to close the fingers in less than two seconds. The resulting motor-gearbox-combinations for the two exemplary hand designs are listed in Table I. This also includes the diameter of the cable pulleys (Pulley D) attached to the gearbox which is basically another gear stage. The general hand platform is equipped with this actuation setup based on motor-gearbox-combinations proposed by the expert system. Thereby it can easily be adjusted to the different requirements of robots for a wide variety of applications. Comparing the specifications of both hands it can be seen that the expert system takes advantage of the larger construction space to select more powerful motors to achieve higher finger forces. The motor-gearbox-pulley combinations of the ARMAR-DE and ARMAR-7 hands have been derived from the expert system and are different from the design of the KIT Prosthetic Hands [33].

The hand platform design is based on a parameterized movable CAD skeleton consisting of planes, axes and sketches that include all joints and hand proportions. Based on parametrized equations the placement of the motor-gearbox combinations, sensors and embedded system are defined. Thereby, the arrangement of mechantronic components is automatically provided for a newly derived hand.

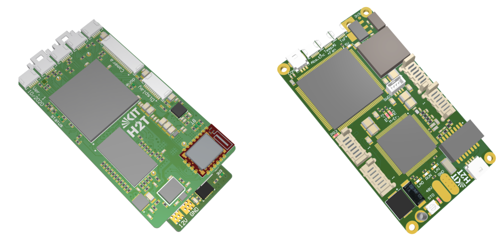
D. Embedded Sensor System

The KIT Robotic Hand platform provides a comprehensive multi-modal sensor system including vision, distance, orientation, temperature and thumb rotation sensors. The placement of these sensors is defined with respect to the hand skeleton in the CAD model. Sensors can be chosen with a varying quality (e. g. different resolutions for the camera) or can be omitted entirely depending on the specific hand requirements. Further, it includes a powerful processing system for in-hand sensor postprocessing and grasp control. Both can be adapted or downgraded to reduce size, cost and power consumption depending on the requirements of a specific hand.

In this work, we present two distinctive variants of the sensor system for the hand of ARMAR-7 and ARMAR-DE, including different processing capabilities. Both embedded systems include motor controllers and can read the position encoder for thumb rotation. The motor drivers of the ARMAR-DE hand (DRV8844, Texas Instruments) use $48\,\mathrm{V}$ input voltage and a maximum current of $2.5\,\mathrm{A}$. The ARMAR-7 version is designed for a lower input voltage ($12\,\mathrm{V}$) and can deliver a maximum current of $2\,\mathrm{A}$ (MP6550, Monolithic Power Systems Inc). The processing system is mounted within the palm, as shown in Figure 3. The housing of the hand protects the PCB from forces and shocks excerted on the hand during manipulation.

Both hands are equipped with an IMU, temperature sensors to survey motor temperature and a Time-of-Flight distance sensor (VL53L5CX, STMicroelectronics) located in the palm. The ARMAR-7 version additionally includes a 5 mega-pixel camera (OmniVision OV5640) for in-hand visual perception. The in-hand camera can provide additional feedback during complex manipulation tasks. To avoid additional high bandwidth camera interfaces through the complete arm structure, in-hand data processing is used for semantic perception.

For in-hand data processing of visual perception data, the hand for ARMAR-7 integrates a hybrid system (XC7020 SoC) including an FPGA and an ARM Cortex-A9 microcontroller. The FPGA is used to implement a CNN hardware accelerator in an adapted version of our previous work [36]. The hybrid embedded system is shown in Figure 4 (a). It is designed as a stack of two PCBs and has the dimensions of $64\,\mathrm{mm} \times 21\,\mathrm{mm} \times 9.9\,\mathrm{mm}$. Compared to the KIT Prosthetic Hands [33], additional temperature monitoring and more powerful processing has been added.



(a) (b)

Fig. 4. Embedded systems of the ARMAR-7 hand (a) and ARMAR-DE hand (b)

The ARMAR-DE hand does not need a camera and local image processing. The embedded processing for ARMAR-DE is focused on motor control, communication on the robot-wide EtherCAT bus system and temperature monitoring. Therefore, the embedded system can be designed much more lightweight and is based on an STM32H7 processor. The hand provides an EtherCAT interface for communication on the robot control bus. The PCB has the dimensions of $38\,\mathrm{mm} \times 70\,\mathrm{mm}$ and is shown in Fig. Figure 4 (b).

V. Evaluation

In order to evaluate the functionality of the adaptive robotic hands, we analyze the hand characteristics and grasping ability. In addition, we point out the added value of integrating computational resources and sensors directly into the hand. First, we measure key characteristics of the hands with respect to speed, force and weight. Further, a general assessment of the hands' grasping ability is performed on a wide range of everyday objects. Finally, the functionality and merit of the customizable processing power and multi-modal sensor system are demonstrated for the application of in-hand image processing.

A. Key Characteristics

The ARMAR-7 hand has the size of the 50^{th} percentile of male hands according to the German Standard Specification (DIN 33402-2). This means that it has a length of $189\,\mathrm{mm}$ and a width of $87\,\mathrm{mm}$. The ARMAR-DE hand is larger to tackle heavy lifting tasks with a length of $246\,\mathrm{mm}$ and a width of $113\,\mathrm{mm}$. The hands weigh $564\,\mathrm{g}$ and $1025\,\mathrm{g}$ for the hands of ARMAR-7 and ARMAR-DE, respectively.

The power grasp force of the hands is measured by grasping a calibrated six-axis force/torque sensor (Mini 40, ATI Industrial Automation) attached within a wooden cylindrical frame ($49\,\mathrm{cm}$ diameter). The hand performs a medium wrap with maximum motor power around the sensor cylinder. The fingers and thumb of the hand connect each to one side of the wooden cylinder and press against the sensor. In order to avoid any interference of gravity, the experiment is carried out with the hand held horizontally and the palm pointing upwards. The hands achieve a power grasp force of $53.4\,\mathrm{N}{\pm}5.6\,\mathrm{N}$ for the ARMAR-DE hand and $45.3\,\mathrm{N}{\pm}12.7\,\mathrm{N}$ for the ARMAR-7 hand, respectively.

The closing speed is measured while closing all fingers of the hand simultaneously at maximum motor power. A video of the hand is recorded and the time between the first motion of the open hand and the last finger stopping in a fully closed fist is measured. Naturally, the middle, ring and little fingers are closing slower than the index and thumb due to the gear reduction of the underactuated mechanism. This asymmetric power grasp motion can fixate an object with thumb and index before fully wrapping around it with the entire hand. A symmetric power grasp motion simultaneously closing all finger of the hand can also be achieved by adapting hand motor control. Overall, the hands close in $1.14\,\mathrm{s}$ for the ARMAR-DE hand and $0.87\,\mathrm{s}$ for the ARMAR-7 hand, respectively.

B. Grasp Success

To evaluate the ability of the hands to grasp objects with a wide range of shapes, textures, sizes and weights, an adapted version of the *YCB Gripper Assessment Protocol* is performed [37]. In contrast to the original protocol, all objects from the *YCB Object Set* except for the task items category are evaluated in order to test the grasp functionality for a broad range of varying objects. To focus on the grasping ability of the hand isolated from the robot arm motion, objects are placed on a table at a fixed location. In order to focus on evaluating the grasping ability of the hand hardware, the robot's arm is guided by a human operator serving as the best possible control. Thereby, problems caused by suboptimal control are elminiated and the achieved grasp success can be directly attributed to the capabilities of the hand hardware. The adapted hand assessment protocol was first used to evaluate prosthetic hands [38].

Each of the 60 objects is placed on a table in front of the robot. Guided by the human operator, the robot moves towards the object and grasps it with the hand. Both power and pinch grasps may be used and the operator chooses the most suitable grasp based on the object's size and geometry. The hand picks up the object from the table and holds it for three seconds. Then the operator rotates the hand by $90°$ and stops for another three seconds. For each object four points can be scored in total. Two points are given if the object can be grasped and lifted, only one point is scored if the object moves within the hand. Similarly, another two points are scored if the object is still securely grasped while rotating the hand. But if the object moves within the hand during the rotation, only one additional point is granted. For soft objects like a rope or a tablecloth, that are not fully immobilized when grasped securely, a different scoring scheme is applied. Instead of four points, a total of 1.5 points are given for a successful grasp without any point deductions for object motion. Overall, 230 points can be achieved.

Based on this protocol, the ARMAR-DE hand achieves an overall grasp success rate of $84.8\,\%$ and the ARMAR-7 hand exhibits a grasp success rate of $88.3\,\%$. The grasp

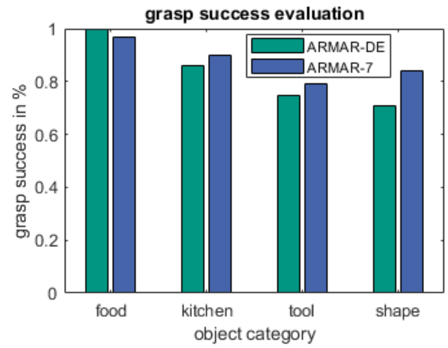


Fig. 5. Grasp success rate of the robotic hands for the different object categories from the YCB Object Set

(a) (b) (c)

Fig. 6. Grasp evaluation with the ARMAR-DE hand grasping a power drill (a) and a clamp (b) and the ARMAR-7 hand grasping a pear (c)

success of both hands for the different categories in the YCB Object Set is presented in Figure 5. Some exemplary grasps with both hands are depicted in Figure 6. The ARMAR-7 hand is more successful in grasping all but the food items. Especially the tool and shape categories include many very small objects and therefore the smaller ARMAR-7 hand is better suited for handling these item categories. The better rating of ARMAR-DE hand in the food category is caused by a higher grasp success on a box of crackers. This box is large, heavy and has a low-friction surface. Therefore, it is easier to grasp for the stronger ARMAR-DE hand. The hand of ARMAR-7 is also able to grasp the cracker box, but the box moves within the hand when turned.

Overall, the delicate, humanoid hand of ARMAR-7 is better in handling small objects, while the larger, stronger hand ARMAR-DE hand does better for very large and heavy objects. To show the grasping ability in the large-scale, hazardous environment the ARMAR-DE hand has been designed for, we grasp three large industrial objects with this hand. These are a metal cylinder of $1.5\,\mathrm{kg}$, an exhaust pipe of $1.4\,\mathrm{kg}$ and a steel channel of $2.0\,\mathrm{kg}$. All three objects can be grasped and rotated securely by the hand. This underlines the capability of the hand to handle large and heavy objects.

C. Image Processing Performance

To evaluate the performance of the embedded system of the ARMAR-7 hand, an image processing algorithm is evaluated using the in-hand camera. We run an 8 bit quantized CNN for image segmentation on the hand internal hardware-accelerator interfaced by the ARM Cortex-A9 processor. We compare its performance to the processor without an accelerator as well as a laptop CPU (Intel i7-8550U). The CNN consists of seven convolutional layers with approximately 14

TABLE II

COMPARISON OF ACCELERATOR PERFORMANCE TO RUNTIME OBTAINED ON AN ARM CORTEX-A9 AND AN INTEL I7-8550U PROCESSOR

Layer (Workload: MAC Ops.)	Cortex A9 Runtime	i7-8550U Runtime	FPGA Acc. Runtime / MAC Ops. s^{-1}	Speedup Acc to A9/i7
Conv 1 (1.368 MOP)	233 ms	24 ms	7.41 ms / 0.184 GOPS	× 31 / 3.2
Pooling Layer 1	4.9 ms	<1 ms	1.31 ms	× 3.7 / < 0.76
Conv 2 (1.824MOP)	284 ms	24 ms	6.95 ms / 0.262 GOPS	× 40 / 3.4
Conv 3 (7.299 MOP)	1104 ms	106 ms	13.56 ms / 0.538 GOPS	× 81 / 7.8
Conv 4 (3.649 MOP)	543 ms	43 ms	3.39 ms / 1.076 GOPS	× 160 / 12.7
Conv 5 (0.114 MOP)	17.7 ms	2 ms	0.42 ms / 0.271 GOPS	× 42 / 4.8
Conv 6 (0.014 MOP)	2.7 ms	<1 ms	0.42 ms / 0.033 GOPS	× 6.4 / < 2.4
Upsampling Layer	0.64 ms	<1 ms	1.22 ms / 0.091 GOPS	× 0.52 / <0.82
Conv 7 (0.114 MOP)	21.6 ms	2 ms	1.24 ms	× 17 / 1.6
Total (14.382 MOP)	2212 ms	204 ms	35.92 ms / 0.400 GOPS	× 62 / 5.7

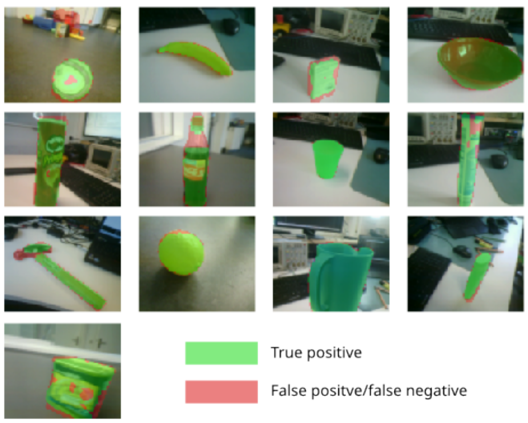


Fig. 7. Pixel wise segmentation obtained from the CNN for several objects captured by the in-hand camera of the ARMAR-7 hand

million multiply-accumulate operations as listed in Table II. The processed camera image of an exemplary pixel-wise object segmentation is shown in Figure 7. For 13 object classes we achieve an IoU of 60.1 % to 95.9 % with a mean value of 80.5 % for all object classes.

Compared to the Arm Cortex-A9 processor the hardware accelerator can achieve a speedup of 62. When comparing the performance of the accelerator to the Intel i7 processor, a speedup of 5.7 is achieved. This demonstrates the merit of a powerful in-hand processing system for image postprocessing. The image processing can be integrated into the grasp control, as shown in our previous work [36].

VI. CONCLUSION

This paper presents the KIT Robotic Hands. The general hand design can be adjusted to accomodate different task requirements. Thereby, it allows to easily derive humanoid hands for robots in a wide range of application areas. The basic kinematic structure and design concept of the hand can be adapted with respect to size, actuation power and sensing modalities. The novel hand platform improves the design of the KIT Prosthetic Hands in terms of grasp variety as well as sensors and processing power, while maintaining the small, human-sized design space. We demonstrate the platform concept on two specific hands for an assistive household robot and a robot for hazardous environments, that are built and evaluated on real humanoids.

The hands have 11 DoF and 4 DoA driving the flexion and rotation of the thumb, the index finger flexion and the flexion of middle, ring and little finger together. These three fingers are driven via an adaptively underactuated mechanism that allows them to wrap around arbitrarily shaped objects. The thumb rotation is equipped with continuous position sensing, which allows to adjust the thumb position beyond basic lateral and opposition grasps. We present a multi-modal sensor system and embedded processing board, that can be adapted to the needs of the intended application. The mechatronic design, including actuation, sensors and processing system, can be scaled to the size and functionality needed for a specific hand.

Both built hands achieve a high grasp force of at least $45.3\,\mathrm{N}$ and can close in less than $1.2\,\mathrm{s}$. They exhibit a grasp success rate of more than $84\,\%$. This shows that the hand platform provides a high functionality, which can further be fine-tuned for the desired application, e. g. by increasing the force of the hand (ARMAR-DE) or optimizing it for grasping smaller objects (ARMAR-7). The merit of the embedded processing system for complex in-hand calculations is demonstrated on an image segmentation algorithm.

With this hand platform, we provide a general basis for a wide range of customized humanoid hands that exploit the full potential of grasping and sensing capabilities possible within the restrictions of the specific robot and application they are designed for. In particular, the vast integration of embedded sensing and processing power allows for local sensor fusion and preprocessing. Thereby, the hand provides the hardware basis for reactive grasping algorithms that rely on local sensors and fast processing to adapt to object motion or erroneous localization while grasping in real-time . In the future, we want to further enlarge the design choices offered by the hand platform. To this end, we will integrate optional force, distance and joint angle sensors in the fingers and an actuation strategy with five motors to allow for tripod grasps. We believe that the presented hand platform is a general tool to build versatile hands for a wide range of applications that provide powerful sensing and computation for autonomous grasp and manipulation control.

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REFERENCES

[1] C. Piazza, G. Grioli, M. G. Catalano, and A. Bicchi, “A Century of Robotic Hands,” *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 2, no. 1, pp. 1–32, 2019.

[2] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, “A compliant, underactuated hand for robust manipulation,” *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.

[3] A. V. Sureshbabu, G. Metta, and A. Parmiggiani, “A new cost effective robot hand for the icub humanoid,” in *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*. IEEE, 2015, pp. 750–757.

[4] A. Nurpeissova, T. Tursynbekov, and A. Shintemirov, “An Open-Source Mechanical Design of ALARIS Hand: A 6-DOF Anthropomorphic Robotic Hand,” in *IEEE International Conference on Robotics and Automation (ICRA)*, 2021, pp. 1177–1183.

[5] G. Gao, J. Chapman, S. Matsunaga, T. Mariyama, B. MacDonald, and M. Liarokapis, “A Dexterous, Reconfigurable, Adaptive Robot Hand Combining Anthropomorphic and Interdigitated Configurations,” in *IEEE/RSJ International Conference on Intelligent Robotic Systems (IROS)*, 2021, pp. 7209–7215.

[6] M. Wang, X. Zhang, M. Zhang, M. Li, C. Zhang, and J. Jia, “Design of TCP-actuator-driven, soft-tendon-integrated anthropomorphic dexterous hand: SoroAgilHand-1,” *Sensors and Actuators A: Physical*, vol. 378, p. 115760, 2024.

[7] N. Fukaya, S. Toyama, T. Asfour, and R. Dillmann, “Design of the TUAT/Karlsruhe Humanoid Hand.” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Takamatsu, Japan, October 30 - November 5 2000, pp. 1754–1759.

[8] M. G. Catalano, G. Grioli, A. Serio, E. Farnioli, C. Piazza, and A. Bicchi, “Adaptive Synergies for a Humanoid Robot Hand,” in *IEEE-RAS Int. Conf. on Humanoid Robots*, 2012, pp. 7–14.

[9] Z. Xu and E. Todorov, “Design of a Highly Biomimetic Anthropomorphic Robotic Hand towards Artificial Limb Regeneration,” in *IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 3485–3492.

[10] T. Asfour, M. Wächter, L. Kaul, S. Rader, P. Weiner, S. Ottenhaus, R. Grimm, Y. Zhou, M. Grotz, and F. Paus, “Armar-6: A high-performance humanoid for human-robot collaboration in real world scenarios,” *IEEE Robotics & Automation Magazine*, vol. 26, no. 4, pp. 108–121, 2019.

[11] N. F. Lepora, C. Ford, A. Stinchcombe, A. Brown, J. Lloyd, M. G. Catalano, M. Bianchi, and B. Ward-Cherrier, “Towards integrated tactile senorimotor control in anthropomorphic soft robotic hands,” in *IEEE International Conference on Robotics and Automation (ICRA)*, 2021, pp. 1622–1628.

[12] H. Li, C. J. Ford, M. Bianchi, M. G. Catalano, E. Psomopoulou, and N. F. Lepora, “BRL/Pisa/IIT Soft Hand: A Low-Cost, 3D-Printed, Underactuated, Tendon-Driven Hand With Soft and Adaptive Synergies,” *IEEE Robotics and Automation Letters (RAL)*, vol. 7, no. 4, pp. 8745–8751, 2022.

[13] C. Melchiorri, G. Palli, G. Berselli, and G. Vassura, “Development of the UB Hand IV: Overview of Design Solutions and Enabling Technologies,” *IEEE Robotics and Automation Magazine*, vol. 20, no. 3, pp. 72–81, 2013.

[14] F. Hundhausen, J. Starke, and T. Asfour, “A soft humanoid hand with in-finger visual perception,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, USA, October 2020, pp. 8722–8728.

[15] R. Deimel and O. Brock, “A compliant hand based on a novel pneumatic actuator,” in *IEEE International Conference on Robotics and Automation (ICRA)*, 2013, pp. 2047–2053.

[16] J. P. King, D. Bauer, C. Schlagenhauf, K.-H. Chang, D. Moro, and N. Pollard, “Design, Fabrication, and Evaluation of Tendon-Driven Multi-Fingered Foam Hands,” in *IEEE International Conference on Humanoid Robots (Humanoids)*, 2018, pp. 1–9.

[17] H. Wang, F. J. Abu-Dakka, T. N. Le, V. Kyrki, and H. Xu, “A Novel Soft Robotic Hand Design With Human-Inspired Soft Palm,” *IEEE Robotics and Automation Magazine*, vol. 28, no. 2, pp. 37–49, 2021.

[18] S. Puhlmann, J. Harris, and O. Brock, “RBO Hand 3: A Platform for Soft Dexterous Manipulation,” *IEEE Transactions on Robotics*, vol. 38, pp. 3434–3449, 2022.

[19] S. Min and S. Yi, “Development of Cable-Driven Anthropomorphic Robot Hand,” *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 1176–1183, 2021.

[20] O. Shorthose, A. Albini, L. He, and P. Maiolino, “Design of a 3D-Printed Soft Robotic Hand With Integrated Distributed Tactile Sensing,” *IEEE Robotics and Automation Letters (RAL)*, vol. 7, no. 2, pp. 3945–3952, 2022.

[21] U. Kim, D. Jung, H. Jeong, J. Park, H.-M. Jung, J. Cheong, H. R. Choi, H. Do, and C. Park, “Integrated linkage-driven dexterous anthropomorphic robotic hand,” *Nature Communications*, vol. 12, p. 7177, 2021.

[22] I. Gaiser, S. Schulz, A. Kargov, H. Klosek, A. Bierbaum, C. Pylatiuk, R. Oberle, T. Werner, T. Asfour, G. Bretthauer, and R. Dillmann, “A new anthropomorphic robotic hand,” in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, Daejeon, Korea, 2008, pp. 418–422.

[23] L. Wang, J. DelPreto, S. Bhattacharyya, J. Weisz, and P. K. Allen, “A highly underactuated robotic hand with force and joint angle sensors,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2011, pp. 1380–1385.

[24] P. Weiner, F. Hundhausen, R. Grimm, and T. Asfour, “Detecting grasp phases and adaption of object-hand interaction forces of a soft humanoid hand based on tactile feedback,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Prague, Czech Republic, September 2021, pp. 3956–3963.

[25] B. Romero, H.-S. Fang, P. Agrawal, and E. Adelson, “EyeSight Hand: Design of a Fully-Actuated Dexterous Robot Hand with Integrated Vision-Based Tactile Sensors and Compliant Actuation,” in *IEEE/RSJ International Conference on Intelligent Robotic Systems (IROS)*, 2024, pp. 1853–1860.

[26] J. M. Romano, K. Hsiao, G. Niemeyer, S. Chitta, and K. J. Kuchenbecker, “Human-inspired robotic grasp control with tactile sensing,” *IEEE Transactions on Robotics*, vol. 27, no. 6, pp. 1067–1079, 2011.

[27] R. Kelly, R. Carelli, O. Nasisi, B. Kuchen, and F. Reyes, “Stable Visual Servoing of Camera-in-Hand Robotic Systems,” *IEEE/ASME Transactions on Mechatronics*, vol. 5, no. 1, pp. 39–48, 2000.

[28] D. Morrison, P. Corke, and J. Leitner, “Learning robust, real-time, reactive robotic grasping,” *The International Journal of Robotics Research*, vol. 39, no. 2-3, pp. 183–201, 2020.

[29] N. Chen, K. P. Tee, and C.-M. Chew, “Teleoperation grasp assistance using infra-red sensor array,” *Robotica*, vol. 33, no. 4, pp. 986—-1002, 2015.

[30] J. H. M. Pereira, C. F. Joventino, J. A. Fabro, and A. S. de Oliveira, “Non-Contact Tactile Perception for Hybrid-Active Gripper,” *IEEE Robotics and Automation Letters*, vol. 8, no. 5, pp. 3047–3054, 2023.

[31] A. Yamaguchi and C. G. Atkeson, “Implementing tactile behaviors using fingervision,” in *IEEE-RAS International Conference on Humanoid Robotics (Humanoids)*. IEEE, 2017, pp. 241–248.

[32] K. Matheus and A. M. Dollar, “Benchmarking grasping and manipulation: Properties of the objects of daily living,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2010, pp. 5020–5027.

[33] P. Weiner, J. Starke, S. Rader, F. Hundhausen, and T. Asfour, “Designing Prosthetic Hands with Embodied Intelligence: The KIT Prosthetic Hands,” *Frontiers in Neurorobotics*, vol. 16, pp. 1–14, 2022.

[34] O. Karrenbauer, S. Rader, and T. Asfour, “An Ontology-Based Expert System to Support the Design of Humanoid Robot Components,” in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, Beijing, China, 2018, pp. 532–539.

[35] S. Rader, “An ontology-based expert system for the systematic design of humanoid robots,” Ph.D. dissertation, Dissertation, Karlsruhe, Karlsruher Institut für Technologie (KIT), 2020, 2020.

[36] F. Hundhausen, S. Hubschneider, and T. Asfour, “Grasping with humanoid hands based on in-hand vision and hardware-accelerated cnns,” in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2023, pp. 0–0.

[37] B. Calli, A. Walsman, A. Singh, S. Srinivasa, P. Abbeel, and A. Dollar, “Benchmarking in Manipulation Research : The YCB Object and Model Set and Benchmarking Protocols,” *IEEE Robotics & Automation Magazine*, vol. 22, no. 3, pp. 184–185, 2015.

[38] P. Weiner, J. Starke, F. Hundhausen, J. Beil, and T. Asfour, “The kit prosthetic hand: Design and control,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Madrid, Spain, October 2018, pp. 3328–3334.