Highly Integrated Sensor-Actuator-Controller Units for Modular Robot Design

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***Abstract*— We present highly integrated sensor-actuator-controller units (SAC units), addressing the increasing need for easy to use components in the design of modern high-performance robotic systems. Following strict design principles and an electro-mechanical co-design from the beginning on, our development resulted in highly integrated SAC units. Each SAC unit includes a motor, a gear unit, an IMU, sensors for torque, position and temperature as well as all necessary embedded electronics for control and communication over a high-speed EtherCAT bus. Key design considerations were easy to use interfaces and a robust cabling system. Using slip rings to electrically connect the input and output side, the units allow continuous rotation even when chained along a robotic arm. The experimental validation shows the potential of the new SAC units regarding the design of humanoid robots.**

I. INTRODUCTION

As robots are complex mechatronic systems, their design is a challenging, expensive and time-consuming task. The reusability of robotic hardware and software components can simplify the design dramatically. This is one of the reasons why considerable research and development activities have been addressing the question of modularity in robotics from software and hardware point of view with the goal of providing components, which can be used for the design of different robot types. In this paper, we present sensor-actuator-controller units (SAC units), which integrate a motor, a gear unit, different sensor types (position, torque, temperature, inertial measurement unit (IMU)), embedded electronics and software for sensor data processing, control and communication.

As there exist numerous actuator units, the following related work is limited to a choice of compact modular rotary actuator units based on an electric motor, which are built for the usage in human-centered robotics applications such as humanoid and service robots. The most prominent example is the the DLR lightweight arm LWR III [1], which integrates compact sensor-actuator joint units and which is the base for the KUKA LBR arms [2]. These units contain a brushless RoboDrive DC motor with a brake, a Harmonic Drive gear unit, position sensors on the motor and the output side of the gear, a torque sensor and an electronic stack for power supply and control. They are placed inside of a carbon fibre hollow (exoskeleton) structure. Recently, the low-cost robot arm FRANKA EMIKA [3] has been introduced, which has a similar appearance and which is also based on modular sensor-actuator units. Universal Robots [4] and Kinova [5] offer other popular commercially available robot arms, that are based on modular sensor-actuator units in different sizes, linked through a hollow structure.

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Fig. 1: Sensor-actuator-controller units in three different sizes

The DARPA Robotics Challenge (DRC) 2015 [6] showed that not only companies, but also many research facilities developing humanoid robots use the advantages of highly integrated, modular sensor-actuator units today. Beside robots based on self-developed sensor-actuator units ([7], [8], [9]), at least seven teams used commercially available Dynamixel units by Robotis [10]. The Dynamixel Pro series offers sensor-actuator units in different sizes, which all include a motor and gear box as well as sensors (incremental and absolute position encoder), a controller and a network module. Furthermore, the units include connectors and flanges for an easy electrical and mechanical integration in robots of a wide variety of physical shapes. This encapsulation and the degree of integration is high, even compared to other commercially available sensor-actuator solutions ([11], [12], [13]). ETH's ANYdrive joint [14] offers another highly integrated sensor-actuator-unit. Compared to other commercially available solutions, it allows precise torque control as it is not based on current control which needs a complex friction model to be reliable.

For safe interaction with humans and the environment, compliance is of utmost importance [16]. Therefore, in the last years, several serial elastic actuators (SEA) have been developed ([7], [8], [14], [17], [18], [19], [20], [21]), which include spring components for passive compliance. Passive compliance has the advantage of inherent reliability since it is realized in hardware. However, compliance parameters are usually fixed and potentially not appropriate for a given interaction task. Furthermore, such passive compliance significantly increases the complexity of control. Another possibility for realizing compliance is active compliance, where compliance parameters are freely adaptable during operation. Based on accurate and fast torque control, the motors are controlled in a way that emulates naturally

TABLE I: Comparison of integrated components and functionalities in state-of-the-art actuator units for robotics

		Source	Motor + Gear Unit	Brake	Absolute Encoder	Torque Sensing	IMU	Slip Ring	Integrated Controller	Communication Bus
Purchasable Actuators	Robotis Dynamixel Pro Series	[10]	●	○	●	CS	○	○	●	CAN, RS-485
	Harmonic Drive CanisDrive	[13]	●	(●)	(●)	○	○	○	○	-
	RoboDrive RD50/70/85-HD	[12]	●	(●)	●	○	○	○	○	-
	Kinova Actuators K-58, K-75, K-75+	[5]	●	○	●	●	○	●	●	RS-485
	Schunk Powercube, PDU, PR, PSM	[11]	●	●	●	○	○	○	●	CAN, Profibus, RS-232
	ETH ANYdrive	[14]	●	○	●	●	○	○	●	CAN
DRC Finalists 2015	WALK-MAN Actuator	[7]	●	○	●	●	○	○	DA	EtherCAT
	RoboSimian Actuator	[9]	●	●	●	○	○	○	DA	EtherCAT, RS-485
	NREC Drive Joint	[8]	●	●	●	●	○	●	○	CAN
Other Actuator Units	DLR LWR III Joint Unit	[1]	●	●	●	●	○	○	DA	SERCOS
	ARMAR-4 Sensor-Actuator Unit	[15]	●	○	●	●	○	○	○	CAN
	KIT Sensor-Actuator-Controller Unit		●	○	●	●	●	●	●	EtherCAT

Symbols: ● = fully integrated; (●) = optional; ○ = not integrated/placed outside
Abbrevations: CS = Torque sensing based on current sensing, DA = Controller is directly attached to the unit, but not encapsulated

compliant behavior. Common techniques for torque sensing in torque control loops are either current sensing [10] or the measurement of small mechanical deformations in the actuator's output part with strain gauges ([1], [15], [18], [22]) or highly accurate position encoders ([7], [8], [20], [21]. For a precise and reliable realization of active compliance, a high control bandwidth is necessary. As elastic elements are low-pass filtering actuation torque inputs, this is contradictory to the structure of SEA [23]. Thus, a stiff actuator with a high-speed control system (using a fast communication bus such as EtherCAT) is the preferable setup for the realization of active compliance.
In this paper, we present our new series of sensor-actuator-controller units (SAC units). Based on our experience with the development of the ARMAR humanoid robots, e.g. ARMAR-4 [15], and insights from literature, we developed highly integrated SAC units in three different sizes (Fig 1), which will be used for the realization of the next generation of the ARMAR robots: Each SAC unit includes a motor, a gear unit and an IMU as well as position, torque and temperature sensors. A microcontroller for sensor data acquisition and a motor control unit are the core parts of an EtherCAT-based control system. Another notable feature is the robust cabling concept, which is designed around a slip ring, allowing continuous rotation of the units when used in robot joints. As a result of the application of our design principles in an iterative electro-mechanical co-design, the SAC units are not only highly integrated (Table I) but also modular, robust and encapsulated.

The remaining of the paper is organized as follows. Section II provides detailed information on the design principles, the electro-mechanical co-design and the resulting SAC units. An experimental evaluation of the functionality of a prototype is presented in Section III. Section IV concludes the paper with an outlook on our planned future work.

II. Design

With the objective of designing easy-to-use actuator units for diverse robotic applications, we defined four design principles: modularity, high integration, robustness and encapsulation. After clarifying these principles, this section describes the electro-mechanical co-design approach we applied for their realization. After an in-depth description of the main components we highlight those components and features that are most affected by the iterative co-design approach. The section concludes with a description of how we designed an entire series of SAC units based on the medium-sized SAC unit, showing the scalability of the approach.

A. Design Principles

1) Modularity: Modularity in the context of robotic actuators describes their ability to be deployed in a variety of configurations. Such configuration range from applications that only require one actuator to complex robots involving many of articulated joints, where the same type of actuator unit might serve as an elbow joint and as a continuously rotating wheel motor. The key components of overall modularity are electrical and mechanical modularity, supported by well-defined interfaces.

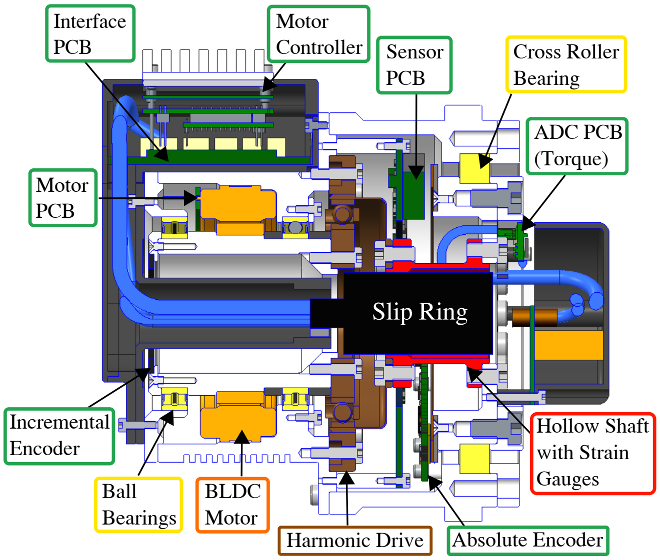

Fig. 2: Labeled cross section of the medium-sized SAC unit

2) High Integration: To facilitate the use of actuator units in different robots and setups, it should be possible to build a robot only by linking actuator units with a minimum of cables and a simple supporting structure. This is why actuators need to be standalone as much as possible both mechanically and electrically. Our new design is based on the sensor-actuator units of ARMAR-4 [15], which include not only the motor and gears, but also sensors for position, torque and temperature sensing. However, the external placement of their control electronics leads to a complex overall cabling and does not support robustness. This is why we aim at building sensor-actuator-controller units that include all electronics for control and communication in an encapsulating housing, exposing only a minimal electrical interface.

3) Robustness and Reliability: Among others, one of the most important goals that modern robotic systems have to reach in order to be widely used, is reliability. In highly integrated, complex mechatronic systems like encapsulated actuators there are multiple potential weak-points that need special attention during the design phase. In addition to mechanical failures which can be avoided by an adequate design and choice of components, the prevention of electronic failures is just as important. Taking countermeasures to eliminate cable breakage and loosening connections, as well as data loss, is mandatory. In the case that errors occur despite those precautions, error detection down to the lowest level needs to be supported.

4) Encapsulation: Closely related to the other design principles, an encapsulated design provides many advantages: It increases the robustness of the system by protecting electronics and other fragile components physically. Furthermore, it can provide the user with an easy-to-use black box if the interfaces are well-designed.

B. Mechanical Design

A cross section of the medium-sized SAC units is shown in Fig. 2. The unit is driven by a brushless ILM 70x10 RoboDrive DC motor [12]. Specifically designed for the use in robotics, these motors combine high torque density with low thermal losses and allow an easy integration into compact actuator units. The rotor sits on the motor shaft that is supported by two suitably sized sealed roller bearings. The shaft turns the wave generator of the CSD-25-160-2A-GR-BB Harmonic Drive reduction gear unit [13]. This gear unit combines a high gear ratio of 160:1 with a compact and lightweight design. Furthermore, the lack of backlash facilitates very precise position control of the actuator. The biggest disadvantage of the Harmonic Drive in this application is its comparatively high internal friction which affects the design of control algorithms for torque-controlled applications. Its output (the flex spline) is linked to a hollow shaft with strain gauges for torque sensing. The hollow shaft (i.e. the torque sensor) is attached to the output flange, which is supported by a sealed cross roller bearing - a compact and rigid solution. All of the structural parts (white) are made out of high-strength aluminum, which combines low density with a high yield strength. Protective covers (dark grey) are made from ABS plastic using 3D printing technology.

C. Sensors

Each SAC unit provides a comparatively large amount of sensory data that can be used in feedback control loops, and for in-depth system monitoring.

All sensor data is available over the high-level bus interface. The motor driver measures and controls the motor current. It is connected to the motor's magnetic incremental encoder (AMS5306) that provides it with 5760 events per motor rotation or 921,600 events per output shaft rotation. All other sensors are connected with digital buses (SPI or I2C) to a central microcontroller. The motor interface PCB includes a 13-Bit temperature-to-digital converter with a temperature range from -40°C to 125°C (Analog Devices ADT7302). The torsional shaft is fitted with four silicon strain gauges on the circumference that are wired to form a temperature-compensated H-Bridge for torque measurement. The analog signal is digitized using a 24-Bit differential ADC (Texas Instruments ADS1220). Information about the absolute position of the output flange comes from a 20-Bit single turn magnetic encoder that features advanced self-monitoring capabilities (Renishaw Aksim MBA8, accuracy $\pm 0.1°$). The sensor board at the heart of the actuator that accommodates the microcontroller for sensor data sampling also features a 9-axes absolute orientation sensing device (IMU) with on-board temperature sensing (Bosch Sensortec BNO055).

D. Electronics

For communications we rely on the Ethernet based EtherCAT (Ethernet for Control Automation Technology), offering real-time performance and a data rate of 100Mbit/s. While the design of internal EtherCAT-enabled electronics is comparatively challenging due to the high signal frequency, the use of EtherCAT supports working with the actuators in a number of ways: First, EtherCAT uses the Ethernet physical layer and therefore works with any standard network interface card. A master control PC does not require any specialized hardware, as it is the case for the majority of other available field bus systems (e.g. CAN or RS485). Secondly, the high bandwidth of 100Base-TX based EtherCAT allows for an high data throughput at high frequencies even on buses with many connected actuators, without the need to worry about reaching the bus capacity limits in most foreseeable applications. This allows to develop and run control loops (such as torque control) on a powerful external master PC, as opposed to relying on the embedded computing system of the SAC unit.

The two core components of the electrical architecture are the motor controller and the microcontroller for sensor data sampling. Both devices are directly connected to the EtherCAT bus and are slaves to the master PC. The motor controller is a very compact industrial grade servo controller for current-, position- and velocity-control, allowing a maximum continuous current output of $10\,\mathrm{A}$ (ELMO Gold Twitter 10/100). It is placed on a specially designed PCB where special care was taken regarding the electrical layout to avoid interference between the high-power traces for motor current on the one hand and the high-frequency communication buses on the other. The sampling microcontroller, located on the sensor PCB at the center of the SAC unit, has two main responsibilities: One of them is running the EtherCAT interface stack, including the EtherCAT state machine. The implemented stack is based on the EtherCAT slave implementation tool provided by Beckhoff, and has been extended with hardware-specific low-level sensor drivers. The other task is periodically sampling all connected sensors (at $1\,\mathrm{khz}$) and maintain an up-to-date representation of all of their readings. We chose an Atmel ATmega1284P microcontroller for this purpose, as it is the simplest and most easy-to-work with controller that fulfills all our requirements. The low-level EtherCAT communication, as well as the physical connection to the bus is implemented with a Microchip LAN9252 EtherCAT Slave Controller (ESC) and dedicated magnetic transformers.

E. Electro-Mechanical Co-Design

In highly integrated SAC units, the position of the sensors and other electronics as well as the cabling need to be carefully taken into account for the mechanical design. In the following, we describe our electro-mechanical co-design with respect to cabling, encapsulation and interfaces.

1) Cabling with a Slip Ring: Actuators with many sensors and other electronic components have a complex wiring system. Vibrations and other movements, commonly present in robotic applications, increase the risk of poor contacts and cable breaks. For a robust actuator, a robust cabling strategy is crucial. Hollow shafts are a popular solution, but this does not prevent motion-induced stress. Furthermore, the maximal rotation of the actuator units is limited due to the cables. A solution for this problem are slip rings: Power and electrical signals are transmitted from brushes to rotating metal rings. This allows a design in which all cables are

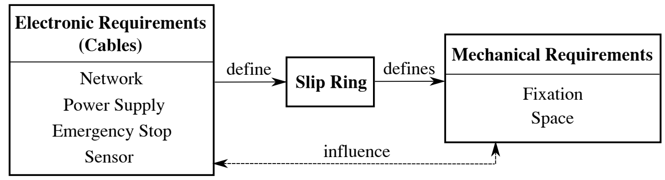

Fig. 3: Example of our electro-mechanical co-design: The slip ring has to fulfill electronic requirements and simultaneously it defines mechanical requirements

fixed and at the same time, an infinite output rotation of the actuator is possible. However, the usage of a slip ring leads to mechanical requirements as well as the slip ring has to fulfill electronic requirements (Fig. 3). Consequently, the design of the actuator unit is heavily influenced by the slip ring's integration, especially since it is placed at the center of the unit (Fig. 2). This was one reason for starting the actuator design simultaneously with concepts for the mechanism and the electronic structure (Fig. 4) with a focus on overlaps between both domains: the installation space, the fixation of all components and the cabling. It became clear that a compact slip ring capsule with dedicated cables for power supply, EtherCAT, emergency stop and the torque sensor is the best choice as it can be placed in a hollow shaft. Based on the first concepts, specific components such as the motor, gear box and sensors were chosen. Only after that the exact requirements could be specified and a slip ring could be chosen. Thereafter, the output shaft, which is fixing the slip ring on one side, could be adjusted as well as other components of the unit. Finally, each cable of the unit was inserted into the CAD model, considering each cable's bending radius and connectors. This lead to further adjustments of the structural parts. In summary, it can be noted that the SAC unit run through repeated iterations between mechanical and electronic design in its early design stage, especially because of the cabling concept. As a consequence, this exact model lead to an easy assembly of the real components without unpleasant surprises. Furthermore, the usage of the slip ring leads to a robust design and offers the possibility of continuous rotation.

2) Output Hollow Shaft: As mentioned before, we use the output hollow shaft with strain gauges for torque sensing. This is why this part has not only to transfer the output torque and to fix the slip ring, but also to be suited for the torque sensing. As a result, there exist contradicting requirements: On the one hand, a stiff design is mechanically advantageous at it makes the shaft more robust. On the other hand, a higher compliance would be better for the accuracy of the torque sensing as a stronger signal can be obtained from the strain gauges. Finally, we decided for a hollow shaft with a spring compliance of about $500\,\mathrm{Nm/degree}$ for the medium-sized actuator. It is made of high-strength aluminium and designed with a safety factor of approximately 2.

3) Encapsulation: Another important element of our strategy for a robust, highly-integrated actuator unit is its encapsulation. All cables and electronic components are hidden and consequently protected from damaging external

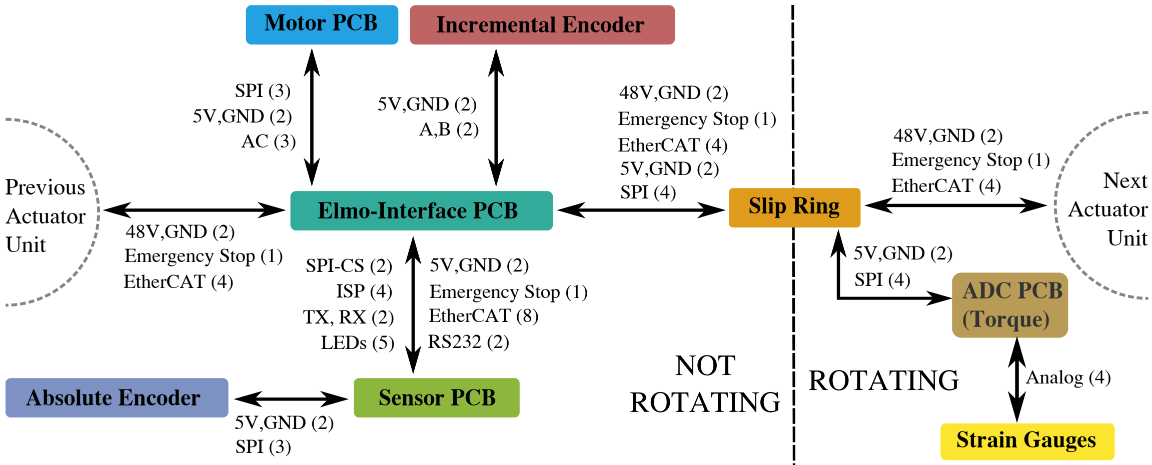

Fig. 4: Overview over the electrical connections between components in the SAC unit. Numbers in brackets indicate the number of wires needed for the particular connection

influences. Similar to the design process described above, the integrated cabling is facilitated by modeling all electronic parts (including the cables) in the CAD model. As shown in Fig. 2, the sensor PCB is placed inside of the housing between the Harmonic Drive and the absolute encoder and therefore completely hidden. The motor controller is placed on an interface PCB with connectors next to the motor. The PCB, the motor controller and the cables on the left side of the slip ring are hidden by protective covers made from 3D-printed plastic. The usage of 3D printed covers offers a large freedom of design for the shape. Furthermore, they can be changed easily, which is very useful for prototyping. So, in this case, the covering for the interface board can be easily adjusted, if electronic parts of the PCB change their placement and dimension. In addition to its function as cover, one part also fixates the left (not rotating) part of the slip ring as well as the PCB of the incremental encoder. Some covering parts on the motor side of the actuator are designed as slide-on parts, allowing an easy access to the interface PCB with its many hidden connectors and cables.

4) Interfaces: For the modularity and usability of actuator units, mechanical and electronic interfaces are of major importance. Mechanically, the actuator unit should offer different integration possibilities. This is why the SAC unit provides not only two screw flanges for the fixation of the housing and the output shaft, but also a second possibility: The cylindrical housing at the output side includes a ring-like part. This ring can be fixed by a clamping counterpart and optionally, a similar interface can be attached to the output flange (Fig. 5, left). Fig. 5 (right) shows a test rig for the elbow of a humanoid robot's arm, which uses both types of mechanical interfaces: The SAC unit for the elbow flexion uses the regular screw flanges, whereas a second SAC unit for the forearm rotation can be integrated using the clamping principle. Electrically, all that the SAC unit needs is access to the communication and the DC bus. Other than an Ethernet and DC-bus patch cable, nothing is needed in order to add another actuator to the chain. The two input connectors are placed tangentially to the housing, allowing a space-saving placement as well as enough place for the cabling. The electrical output interface consists of the same connector plugs that are placed centrally (Fig. 5, left). The diameter of the 3D-printed cover still allows the usage of the output flange, if a borehole is used. Alternatively, two cables can replace the output connector, allowing a shorter length of the SAC unit (Fig. 5, right). Besides the DC bus and the high-level EtherCAT connectivity for regular operation, the actuator exposes an optional emergency stop cable and a number of additional electrical interfaces. All of these interfaces are available over dedicated plugs on the interface board when the protective plastic cover is removed. The motor controller and the microcontroller board both have a TTL-level interfaces for bidirectional serial communication. This feature can be used for low-level debugging, but also as a way to connect the actuator to hardware that is not capable of EtherCAT. For directly connecting a PC to the ELMO drive via USB, the board also offers a standard mini-USB plug. This is especially useful for initial setup and configuration of the controller.

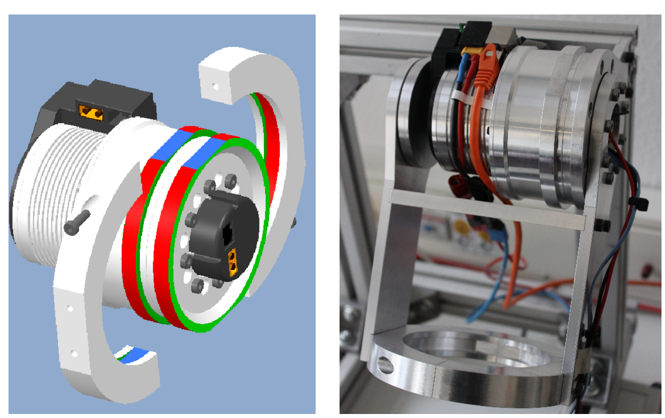

Fig. 5: Mechanical interfaces: Clamp ring interface highlighted in red (left); Flange interface used in an elbow joint (right)

5) Installation and Maintenance: Due to the integration of all electronic components in the CAD model, the assembly and disassembly process could be taken into account throughout all of the design process. The result is a unit which can be disassembled comparatively easy despite its high degree of integration.

F. Scalability

As robotic joints encounter application-specific requirements, we designed three sizes of SAC units. Scalability in the sense of using the same components for differently-sized actuators simplifies the design phase. For the development of the large SAC unit we used the Harmonic Drive CPL-2A units that have a higher maximum torque than the shorter CSD-2A units, while having the same diameter[13]. As there also exist longer RoboDrive motors[12] with the same diameter but higher nominal torques (ILM 70x18), we only had to lengthen the medium actuator unit to get a unit with a higher torque capacity. As we did not have to change the diameter of the SAC unit, we could reuse each of our five PCBs with all their components, all remaining sensors and the bearings. Thus, the electrical setup for the large unit is identical to the setup described above. Furthermore, five out of the ten aluminum parts are exactly the same. The remaining five parts only differ in few parameters, mostly in the length. This strategy does not only reduce the costs and time for design but also shortens the testing period. The third member of the SAC unit series is the small SAC unit with a ILM 50x08 motor and a CSD-20-160-2A-GR-BB Harmonic Drive. As we wanted to reduce the diameter (a critical dimension for most components) compared to the medium-sized SAC unit, the re-usability of the parts could not be realized the same way. However, we still used the same components or their smaller version as well as the exact same cabling concept. As shown in Table II, the small-sized SAC unit roughly shares its length with the medium-sized SAC unit, whereas the medium-sized and the large-sized SAC unit share their maximum diameter. The peak torques of the SAC units correspond to the limits for repeated peak torques of the Harmonic Drive units. Based on these limits, static analyses for every part are conducted to ensure a safety factor $S = 2$ against plastic deformation.

SAC Unit	Peak Torque [Nm]	Max. Speed [°/s]	Ratio	Weight [kg]	Length [mm]	Diameter [mm]
Small (S)	64	206	160	1.1	117	85
Medium (M)	123	132	160	1.8	113	112
Large (L)	176	79	160	2.2	159	112

TABLE II: SAC unit specifications

III. EVALUATION

To evaluate our design, we built a first medium-sized sensor-actuator-controller unit and conducted a series of tests. Fig. 6 shows our test rig: The SAC unit on the right side is mechanically linked to an electrodynamic brake on the left side that produces a torque that is proportional to the rotational velocity. As presented in Section II, the SAC unit only needs two cables: A standard Ethernet cable (100BASE-TX) for the EtherCAT bus links the unit with a PC, while a supply unit provides power over the power cable. The cables at the output, which are not needed for this test, rotate at output speed and are therefore fixed to the coupling.

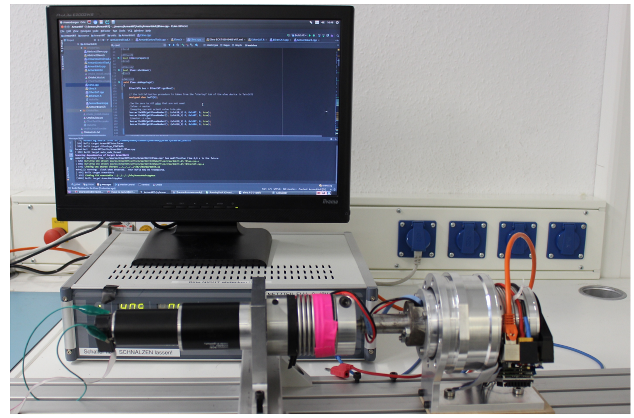

Fig. 6: Test rig for the SAC unit. The SAC unit on the right is connected to an electrodynamic brake on the left (black) by a bellows coupling

To verify the functionality of the torque sensor during operation of the SAC-unit at different rotational speeds we let the actuator track a given velocity profile while measuring the brake torque with the actuator's torque sensor. As presented in Fig. 7, the torque sensor reveals the expected proportional correlation between speed and torque: When scaled appropriately, the torque induced by the electrodynamic brake measured by the SAC-unit's torque sensor (orange dashed) very closely follows the measured rotational velocity (black). This also indicates correct operation of the slip ring that conducts the digitized torque signal from the sensor.

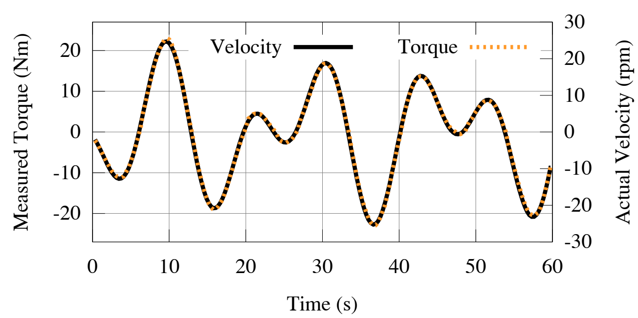

Fig. 7: Rotational velocity and measured torque during a velocity tracking experiment (scaled to match). The proportionality between the two values indicates correct functioning of the torque sensor

The second test aims at determining the actual resolution of our torque sensor. Therefore, we attach a coin with a mass of $7.5\,\mathrm{g}$ on a lever arm attached to the output at a distance of $54.3\,\mathrm{cm}$ to the actuator's axis. At some point in time the coin is dropped, resulting in a change in torque of $0.04\,\mathrm{N\,m}$. The resulting torque curve shown in Fig. 8 indicates a resolution even higher than the $0.04\,\mathrm{N\,m}$ and a noise bandwidth of approximately $0.04\,\mathrm{N\,m}$.

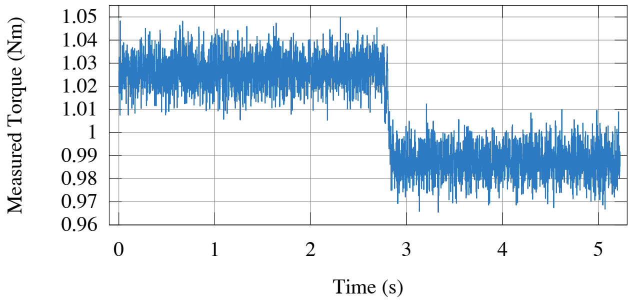

Fig. 8: Torque sensor response to a sudden change in the applied torque of $0.04\,\mathrm{N\,m}$

IV. CONCLUSION

We presented a new series of modular sensor-actuator-controller units (SAC units) with a focus on applications in humanoid robots. A main feature of the SAC units is the high degree of integration as they include a motor, a gear box and a comprehensive sensor system, as well as electronics for communication and control over EtherCAT, in an encapsulated design. We discussed the underlying design principles and described the electro-mechanical co-design which we followed strictly from the beginning on. We demonstrated the scalability of the approach by realizing the actuator design in three different sizes. Finally, we evaluated a prototype of the SAC unit in a test rig and presented first experimental results. Future work will include further tests of the SAC units as core components of the high-performance KIT dual arm robot [24], see Fig. 9, and the investigation of different torque control strategies.

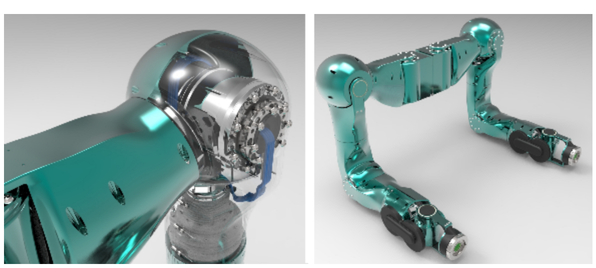

Fig. 9: SAC units in the KIT dual arm robot

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REFERENCES

[1] A. Albu-Schäffer, S. Haddadin, C. Ott, A. Stemmer, T. Wimböck, and G. Hirzinger, "The DLR lightweight robot - Design and Control Concepts for Robots in Human Environments," *Industrial Robot: An International Journal*, vol. 34, no. 5, pp. 376–385, 2007.

[2] "KUKA Robot GmbH". A revolution in robotics. With a sensitive touch. LBR iiwa. [Online]. Available: http://www.kuka-healthcare.com/NR/rdonlyres/310A3034-1F44-47D7-8B37-F681BFCF7757/0/db_LBRiiwa_en.pdf

[3] "FRANKA EMIKA". [Online]. Available: https://www.franka.de/

[4] "Universal Robots". [Online]. Available: http://www.universal-robots.com

[5] "Kinova Robotics". [Online]. Available: http://www.kinovarobotics.com

[6] DARPA Robotics Challenge Finals 2015. [Online]. Available: http://archive.darpa.mil/roboticschallenge/

[7] F. Negrello, M. Garabini, M. G. Catalano, J. Malzahn, D. G. Caldwell, A. Bicchi, and N. G. Tsagarakis, "A Modular Compliant Actuator for Emerging High Performance and Fall-Resilient Humanoids," in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2015, pp. 414–420.

[8] A. Stentz, H. Herman, A. Kelly, E. Meyhofer, G. C. Haynes, D. Stager, B. Zajac, J. A. Bagnell, J. Brindza, C. Dellin, M. George, J. Gonzalez-Mora, S. Hyde, M. Jones, M. Laverne, M. Likhachev, L. Lister, M. Powers, O. Ramos, J. Ray, D. Rice, J. Scheifflee, R. Sidki, S. Srinivasa, K. Strabala, J.-P. Tardif, J.-S. Valois, J. M. V. Weghe, M. Wagner, and C. Wellington, "CHIMP: the CMU Highly Intelligent Mobile Platform," *Journal of Field Robotics*, vol. 32, no. 2, pp. 209–228, 2015.

[9] P. Hebert, M. Bajracharya, J. Ma, N. Hudson, A. Aydemir, J. Reid, C. Bergh, J. Borders, M. Frost, M. Hagman, J. Leichty, P. Backes, B. Kennedy, P. Karplus, K. Byl, B. Satzinger, K. Shankar, and J. Burdick, "Mobile Manipulation and Mobility as Manipulation - Design and Algorithms of RoboSimian," *Journal of Field Robotics*, vol. 32, no. 2, pp. 255–274, 2015.

[10] "ROBOTIS INC". [Online]. Available: http://www.robotis.com

[11] "SCHUNK". [Online]. Available: http://www.schunk.com

[12] "TQ-Systems GmbH". [Online]. Available: http://www.robodrive.com

[13] "Harmonic Drive AG". [Online]. Available: http://harmonicdrive.de

[14] "ETH Zürich". ANYdrive robot joint. [Online]. Available: http://www.rsl.ethz.ch/robots-media/actuators/anydrive.html

[15] T. Asfour, J. Schill, H. Peters, C. Klas, J. Bücker, C. Sander, S. Schulz, A. Kargov, T. Werner, and V. Bartenbach, "ARMAR-4: A 63 DOF Torque Controlled Humanoid Robot," in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2013, pp. 390–396.

[16] B. Vanderborght, A. Albu-Schäffer, A. Bicchi, E. Burdet, D. G. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, M. Garabini, M. Grebenstein, G. Grioli, S. Haddadin, H. Hoppner, A. Jafari, M. Laffranchi, D. Lefeber, F. Petit, S. Stramigioli, N. Tsagarakis, M. Van Damme, R. Van Ham, L. C. Visser, and S. Wolf, "Variable impedance actuators: A review," *Robotics and autonomous systems*, vol. 61, no. 12, pp. 1601–1614, 2013.

[17] N. G. Tsagarakis, M. Laffranchi, B. Vanderborght, and D. G. Caldwell, "A Compact Soft Actuator Unit for Small Scale Human Friendly Robots," in *IEEE International Conference on Robotics and Automation*, 2009, pp. 4356–4262.

[18] L. Vo-Gia, N. Kashiri, F. Negrello, N. G. Tsagarakis, and D. G. Caldwell, "Development of a 7DOF Soft Manipulator Arm for the Compliant Humanoid Robot COMAN," in *IEEE/RAS International Conference on Robotics and Biomimetics*, 2014, pp. 1106–1111.

[19] X. Huo, Y. Xia, Y. Liu, L. Jiang, and H. Liu, "Humanoid Arm with the Integrated Serial Elastic Actuator," in *IEEE International Conference on Robotics and Biomimetics*, 2014, pp. 2321–2326.

[20] M. A. Diftler, J. S. Mehling, M. E. Abdallah, N. A. Radford, L. B. Bridgwater, A. M. Sanders, R. S. Askew, D. M. Linn, J. D. Yamokoski, F. A. Permenter, B. K. Hargrave, R. Platt, R. T. Savely, and R. O. Ambrose, "Robonaut 2 - The First Humanoid Robot in Space," in *IEEE/RAS International Conference on Robotics and Automation (ICRA)*, 2011, pp. 2178–2183.

[21] N. A. Radford, P. Strawser, K. Hambuchen, J. S. Mehling, W. K. Verdeyen, S. Donnan, J. Holley, J. Sanchez, V. Nguyen, L. Bridgwater *et al.*, "Valkyrie: NASA's First Bipedal Humanoid Robot," *Journal of Field Robotics*, vol. 32, no. 3, pp. 397–419, 2015.

[22] J. Englsberger, A. Werner, C. Ott, B. Henze, M. A. Roa, G. Garofalo, R. Burger, A. Beyer, O. Eiberger, K. Schmid, and A. Albu-Schäffer, "Overview of the Torque-Controlled Humanoid Robot TORO," in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2014, pp. 916–923.

[23] G. A. Pratt and M. M. Williamson, "Series Elastic Actuators," in *IEEE/RSJ Int. Conf. Intell. Robots Syst. Human Robot Interaction Cooperative Robots*, vol. 1, 1995, pp. 399–406.

[24] S. Rader, L. Kaul, H. Fischbach, N. Vahrenkamp, and T. Asfour, "Design of a High-Performance Humanoid Dual Arm System with Inner Shoulder Joints," in *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*, 2016, pp. 523–529.