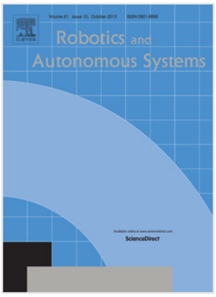

Towards a fine manipulation system with tactile feedback for deep-sea environments

Peter Kampmann, Frank Kirchner

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**Research Highlights**

- overview state of the art underwater manipulation
- design presentation of a multi-limb fine-manipulation system with tactile feedback
- description of hydraulic, electronic and software systems
- presentation of suitable tactile sensors for deep-sea missions
- presentation of experiment results testing the tactile sensor under 600 bar ambient pressure

# Towards a fine manipulation system with tactile feedback for deep-sea environments

Peter Kampmann[a], Frank Kirchner[a,b]

[a]German Research Center for Artificial Intelligence (DFKI) ,Robert-Hooke-Str. 5, D-28359, Bremen, Germany
[b]Robotics Group, University of Bremen, Robert-Hooke-Str. 5, D-28359, Bremen, Germany

## Abstract

Deep-sea manipulation is among the most challenging tasks in underwater robotics. Commonly used manipulation systems consist of a two-limb gripper system with limited force-feedback. Poor viewing conditions due to hazy water and missing depth information complicate the execution of manipulation tasks. By looking at the variety of different tasks that need to be fulfilled a design for a multi-limb gripper system is derived that is equipped with tactile sensors which allow fine-manipulation tasks. The feasibility of the described approach is demonstrated by testing one finger of the manipulation system in a pressure chamber under 600 bar.

*Keywords:* tactile sensors, manipulation, deep-sea, preprocessing of tactile data

## 1. Introduction

The extraction of mineral resources as well as oil and gas is taking place in deep-sea environments. Future applications and harvesting methods demand complex construction and maintenance capabilites at ground-sea level. Tasks that have been performed by divers beforehand, now have to be executed by underwater robots with high manipulation skills because the operational area is beyond the reach of divers.

Compared to robotic systems on land, the development of tools for manipulation tasks has not reached the same technological maturity yet. Although operators of remotely operated vehicles can perform astonishing tasks with industrial deep-sea manipulators, there is a lack of tactile feedback during manipulation, which would have several advantages. Most deep-sea manipulation systems can only be monitored by cameras attached to the robotic vehicle, so in many cases, there is a lack of depth information. When operating at ground-sea level or in port environments, hazy water causes poor viewing conditions which adds complexity to the manipulation tasks or makes them impossible. Tactile feedback will supply the operator with a sense of touch which will allow the execution of manipulation tasks under the described conditions. Some works towards tactile fine-manipulation grippers have been undertaken to overcome this lack of sense [1],[2] and [3], but those systems are either rated for depth that is far from the deep-sea area (deep-sea is referred to the border of the continental shelf at roughly 200 m water-depth [4]) or do not have enough gripping force for performing tasks in a real-world environment. First attempts towards force feedback in the end-effector itself for industrial grippers are reported in [5] where an industrial manipulator has been equipped with a vibrotactile feedback. It is stated that different kinds of material hardness could be distinguished during grasp thanks to vibractile feedback.

In the follwing we present our approach to a fine-manipulation gripper system. After giving an overview about common underwater manipulation tasks we show that a two-limb manipulation system is not the ideal tool for those operations. We derive our multi-limb structure based on those observations and present the morphology and actuation system of the proposed gripper. We proceed by giving an overview of the requirements on our tactile sensory system and the sensor principles we chose for fulfilling these requirements at 600 bar ambient pressure. The challenges on processing the huge amount of sensor information together with transmitting them to higher-level control layers is described in the section about the processing architecture of the system. Finally, we show the feasibility of the results already achieved by testing one finger of the manipulation system in ambient pressure of 600 bar in the pressure chamber of the DFKI Robotics Innovation Center.

## 2. System Design

### 2.1. Morphology Decisions

Common underwater manipulation systems consist of a seven degree of freedom hydraulic manipulator with a two-limb end-effector without any tactile feedback. An investigation of current manipulation tasks that are perfomed in deep-sea environments shows that this cannot be the ideal tool for those tasks. Although traditional underwater intervention tasks that are handled by manipulators in the industrial sector can be summarized to drilling, cutting [6], inspection and cleaning [7], these tasks become much more complex in emergency cases like in the Deepwater Horizon incident or generally in scientific operations. Tasks like sampling, coring, connector-mating [8], moving levers, opening boxes, rolling out of cables as well as handling scientific equipment are common challenges in the marine science area. Apart from the complexity of the manipulation tasks itself, other conditions like poor visibility due to hazy water conditions or the lack of depth information due to supervision of the operating scene through cameras complicate the operations.

Remotely operated vehicles are considered to perform the work divers do in deep-sea environments [9], [10], [7]. Until now, these systems lack the capabilities of the human hand which acts as a general purpose tool for divers in order to handle objects by various grasp types and tactile feedback. As mentioned in [11] and [12] the morphological complexity of a gripper system increases with the amount of grasp types that the gripper should be capable of. For the morphological design it becomes therefore important, which grasp types the robotic gripper system should be able to perform. According to [12] many of the grasp types that are used in manipulation with the human hand can be realised by a robotic gripper system with an artificial setup consisting of three fingers with two opposable thumbs. This morphology is a classical design for robotc grippers [13] in terrestrial domains.

The amount of limbs at each end-effector module determines the ability to perform form-closure grasp operations. An ideal prototype of a limb structure for a form-closed grip from biology seems to be the tentacle of an octopus which is able to adapt smoothly to a variety of shapes based on its many degrees of freedom. A morphologic structure which comes close to this, are end-effectors based on the fin-ray effect which are implemented in a gripper system in [14]. A drawback of this approach is its limited force-closure grasp possibilities. Thus, a trade-off between good force-closure and form-closure structures is desirable.

Based on these considerations, we present our gripper system which is designed as a three-finger multi-limb system with two opposable thumbs as can be seen in figure 1.

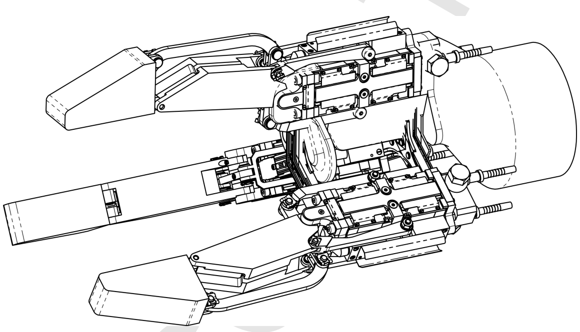

Figure 1: Morphology of the final SeeGrip Manipulation System

### 2.2. Actuation principle

In order to use existing infrastructure on remotely operated vehicles, a hydraulic actuation system was chosen. This allows for using the designed gripper system as an end-effector module for most available deep-sea manipulators. The structural parts of the gripper that come in direct contact with the handled objects should reserved for tactile sensor elements as much as possible. Therefore, the actuation modules of the gripper system have been moved to the lower parts of each limb (see. Fig. 2).

Concerning the forces the system should be able to apply, no absolute values do exist that could be used as a reference. The system is designed for fine manipulation tasks which results in a much weaker system than traditional underwater manipulators that exert forces of 5000 N and more. Comparing the state of the art of underwater grippers, the gripping force of 15.45N at the fingertip [15] of the AMADEUS hand or roughly 8N for the fingertips of the HEU Hand II [3] seem to be not enough for tool handling or common pick and place tasks under water. As the energy source for the actuation has been defined to be coming from the hydraulic supply that is available on most ROVs due to the hydraulic manipulator arm, the gripper can be equipped with high forces. Therefore, the actuator modules have been specified to exert a maximum gripping force of 100 N at the fingertips.

Due to the effect of induced inertia on the robotic system that is carrying the manipulation device, movements of underwater manipulation devices tend to be slower compared to their counterparts on land. As free objects move slow through the water column caused by their bouyancy together with the fact that underwater manipulation tasks are generally not monotonous like automation handling operations in production halls, fast limb movements are not the main focus while designing such systems. The SeeGrip gripper system is designed to open and close the gripper with 0.2 Hz and a repeatable precision of 1 degree minimum.

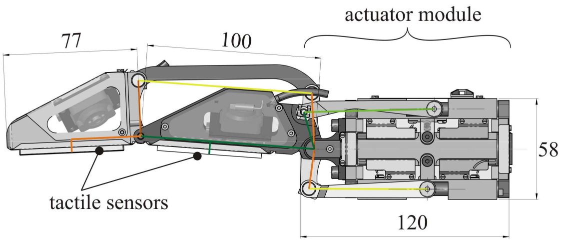

Figure 2: Detailed graphics of the finger module

The dimensions shown of the finger modules (in millimeters) make it clear, that even the use of commercially available sub-miniature hydraulic servo-valves are too big to be integrated into the system. As the proposed gripper system is meant to be used for fine-manipulation tasks, the rated flow needed for precise movements of the gripper is much lower than what those valves are rated for. For that reason, our proposed hydraulic circuit for one piston of the gripper system consists of four 2/2-way micro solenoid valves. Experiments show, that this setup suits the requirements with respect to size, precision of movements and applicable force. A detailed description of the working principle of the actuation module of the gripper system including the modelling of a passive-compliance for the gripper is available in [16].

### 2.3. Electronic system

All control and sensor data processing should be done directly in the gripper system. The goal of this approach is to move the processing load from a centralized external control unit to several decentralized embedded devices which are distributed throughout the gripper system. Especially when working with dense tactile sensor information this approach becomes necessary to face the challenge of processing the huge amount of data that is coming from the sensors. Ideally, the data is processed directly where the data is recorded. For that reason, electronic interfaces and processing devices will be included directly in the finger modules.

Another important aspect of this approach is the realisation of a simple interface to the higher level processing units and for the needed hydraulic as well as electric supplies. Currently, the system is designed to have three input and output connections. The data going to and from the gripper will be transmitted via ethernet, all printed circuit boards (PCBs) in the gripper system are prepared to work with a common input voltage supply. Figure 3 shows the electronic set-up for the manipulator.

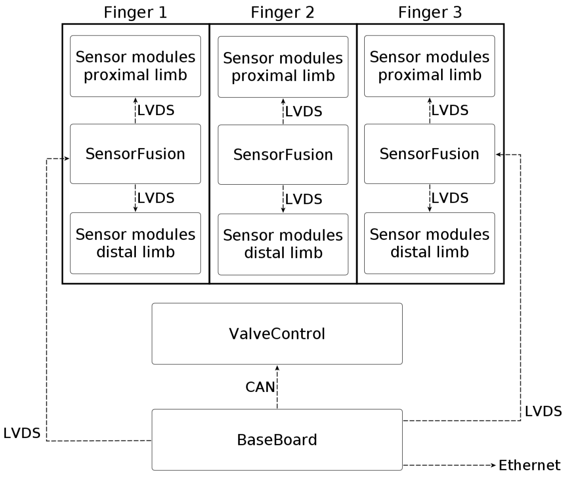

Figure 3: Schematic of the electronic modules in the gripper system

All incoming control and request messages from processing modules outside the gripper itself are processed at the *BaseBoard* of the system. This PCB consists of a digital signal processor (DSP) which communicates with a field programmable gate array (FPGA). The motor control commands are sent via controller area network (CAN) from the DSP to the *ValveControl* electronics. This processing module handles the pulse-width modulation signal generation for the twenty-eight valves for the whole system as well as the control. The FPGA on the *BaseBoard* handles the communication with the *SensorFusion* modules in the end-effectors using a full-duplex low-voltage differential signaling line. The *SensorFusion* Board itself is equipped with a FPGA which serves as a sensor data collection and preprocessing device for the sensor data coming from the upper and lower limb of the finger.

Concerning the encapsulation of the electronic modules for underwater use, attention has to be paid on electronic components that might contain cavities filled with air in their package. For this reason the use of electrolytic capacitors which are used for higher capacities has to be avoided. These components can be replaced by stacks of capacitors that have been manufactured as surface mounted device components. Furthermore, crystal oscillators with nitrogen based packaging need to encapsulated from the ambient pressure. As most of the SMD components are bubble free [17], encapsulated printed circuit boards using a coating of silicone and epoxide resin have been successfully tested under 600 bar ambient pressure.

## 3. Sensor system

As this gripper system should support deep-sea intervention tasks by giving tactile feedback to overcome the lack of depth information and to work even under poor viewing conditions much attention is paid on the design of the sensor system of the gripper.

Similarities in this desired property of the gripper system can be seen in the ability of humans to operate in complete darkness and identifying grasped objects by the tactile afferent information coming from the mechanoreceptors of the human skin. Those mechanoreceptors are subdivided into four different groups which are specialised to specific kinds of sensory modalities, they respond to different stimulus frequencies and are unevenly distributed across the skin [18]. Additional information like temperature, tension developed by muscles or cutaneous afferents on the hairy skin is used and fusioned to identify grasped objects.

Several papers deal with the development of artificial skins [19], [20] and [21]. Most of these keep their focus either on high spatial density, minimizing wiring effort and adaptability to be used as a covering for the whole robot. The approach of using different sensor types that are specialised in their measurement principle to sense different kinds of input forces as one sensor system has not been deeply investigated until now.

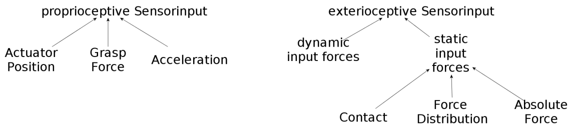

Figure 4: Sensory input to the processing units of the gripper system

Figure 4 shows the proprioceptive and exterioceptive signals the designed manipulation system should be able to measure. Most of the proprioceptive information can be perceived in a straight forward way. Absolute angular encoders will be used for the actuator position measurements, the acceleration of the system can be measured by using small scale inertial measurement units and the grasp force can be calculated by measuring the rated flow of the hydraulic actuators.

The object properties that should by gained by the gripper as shown in diagram 4 require sensors that are able to sense static and dynamic forces with spatial resolution. Thus, principles have to be identified, which can sense these modalities in a sensor field configuration.

Unlike robotic gripper systems on land, that are equipped with tactile feedback, the sensor principles used here need to be working while exposed to the pressure of the water column. Thus, sensors are required that work as relative force or pressure sensors. Common sensor principles that are used in tactile fields like capacitive sensors as they are used in [22] and [23] as well as sensors which use the force sensing resistor principle [24] or use conductive rubber [25], [26] cannot be used.

A measurement principle that is known to be working well under ambient pressure is the use of the piezoelectric effect. Applications range from sonar transducers, pressure sensors, flow meters [27] to sensors for underwater robotic systems [1]. As the sensor response is especially good for dynamic stimuli this measurement principle is chosen for the dynamic force measurement of the system.

Absolute forces are typically measured using strain gauge sensors. Like for the piezoelectric sensors, there are already existing applications in the underwater domain. Common applications are depth measurement [28] and robotic applications [29]. In order to measure the absolute incoming force vectors to the gripper system, strain gauge sensors will be used in the structure.

For the measurement of force distribution and contact points a sensor array is needed. Due to their resistance against water and robustness against ambient pressure, sensor fields based on fiber optic measurement principles seem promising to be used in the deep-sea. First attempts to realise tactile fields using optical sensors for underwater use are reported in [30]. In this work a tactile sensor is proposed that reacts to sliding objects on the sensory surface. The deflection of a roller element that comes in contact with the manipulated object corresponds directly with the output power of the optical fiber. For a sensor field that covers a complete gripper system, this approach seems quite complex and the bending structure is prone to defects.

Another sensor principle based on fiber-optic sensing [31] that has not been used under water until now but has the properties to be able to work under ambient pressure is shown in figure 5.

The main components of these sensors are some polymer foam material, one optical fiber that emits light into the foam and an additional optical fiber that senses the reflected light from the foam. In the neutral state of this configuration (as can be seen in the upper part of figure 5), the light is emitted into the foam and scattered.

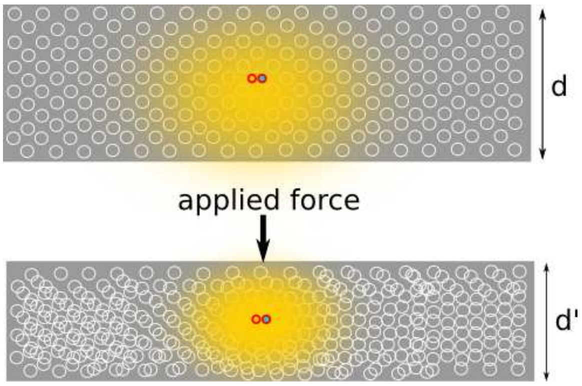

Figure 5: Working principle of the fiber optic sensor

In this configuration only a little amount of light is collected by the sensing fiber. As the foam is compressed, the light is scattered in a smaller area of the foam which results in an increase of light that is going through the sensing optical fiber.

This approach has several properties which make it an ideal candidate for a tactile field for deep-sea environments. The mechanical signal transmission through the foam is independent of the ambient pressure caused by the water column when using an open-cell structure for the foam. The use of polymer optical fibers as light emitting and sensing devices is also independent of ambient pressure as those fibers do not have air inclusions. Furthermore, no electric components need to be placed at the force induced area as the light can be transmitted nearly without attenuation to any desired position in the gripper system.

Apart from most other sensors that base on an optic measurement principle, this approach does not require any complex processing electronics. For the light emission into the foam each light emitting fiber can be attached to a LED. The sensing part of the system can be realised by a phototransistor for each sensing LED which would result in a quite bulky electronic setup when using some hundreds of sensor elements. A more compact and also easier to handle from the processing side is the use of one or more CMOS camera chips as signal converters from brightness to electrical processable input. This approach has been reported first in [32] and has been refined and simplified using cheaper camera-systems and advanced processing algorithms [33]. As the sensor principle is not prone to electromagnetic fields, the influence of noise signals on the sensor is low. During the manufacturing of the sensor modules blackened epoxy resine is used to attach the optical fibers to the camera module. A skin made of black rubber material is covering the sensor array, thus shielding any ambient light from the sensor. Some noise is introduced into the system at the camera where the signal is converted from light to electricity. This noise comes from the CMOS sensor and is independent of the ambient pressure. While averaging neighbouring pixel values of a sensor element in one image, this noise is lower than 0.5% of the signal range of the camera.

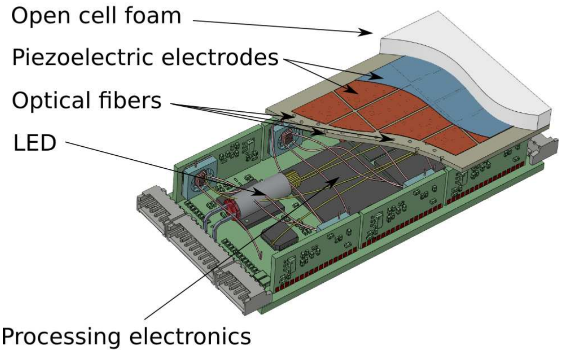

Figure 6: Illustration the proposed tactile sensory system with local preprocessing

This measurement principle will be combined together with the use of piezoelectric sensors to a sensor system that is able to sense static and dynamic forces at the same contact area. Figure 6 shows a drawing of the proposed system. Going from top to bottom, the upper layer shows the open-cell foam which serves as the signal converter from mechanical deformation to light emission of the fiber-optic sensor. The next layer coloured in blue shows the ground plane of the piezoelectric sensor field. This plane together with the electrode fields that lie underneath is covered with holes for the optical fibers. The sensing fibers of the fiber-optic sensor elements are interfaced by six CMOS camera chips which are capable to process roughly 60 sensor elements each. The cameras are controlled and processed by a FPGA. The piezoelectric sensor field is interfaced by a programmable system-on-chip module which belongs to the class of mixed signal electronics. In the complete configuration, this sensor setup is capable of processing 324 fiber optic sensor elements and 20 piezoelectric sensor elements on each of the modules shown in figure 6. The modules have a dimension of six by three centimeters and fit into the upper and lower limbs on each finger of the gripper system. The absolute force measurements using strain gauge sensors as described before will be realised by applying printed strain gauge sensors [34] to the structure of the gripper system. This technique uses the mechanical structure also as part of a sensing device which allows a space-saving solution to integrate a distributed force sensor in the finger structure. These strain gauge sensors will be interfaced by mixed-signal electronics. Together with four temperature sensors in each finger the described sensors build the sensory part of the gripper system. Depending on the final configuration between 700 and 2100 single sensor signals will integrated into the system which need to be processed.

## 4. Processing architecture

The sensor information perceived by the gripper system needs to be processed, enriched and fusioned to support the operators with valuable information during manipulation tasks as well as to perform autonomous exploration. By realising local preprocessing units near the sensor elements itself the computational load is balanced throughout the processing chain. This decentralized approach increases the available computing time for complex algorithms on high-level layers of the data processing.

Besides gaining higher level information, local preprocessing of the data including data reduction or signal suppression is needed by applying simple compression techniques and modeling expected sensory feedback. In graphic 7 the approach of sensor fusioning and data reduction to address one of the challenges in handling large tactile sensors is shown.

At the lowest level the sensor information is perceived and fed through filter modules. The following algorithms extract high-level information from the gained data which is used as input for algorithms in the reactive and deliberative layers similar to [35]. This kind of structure is common in robotic software architectures [36].

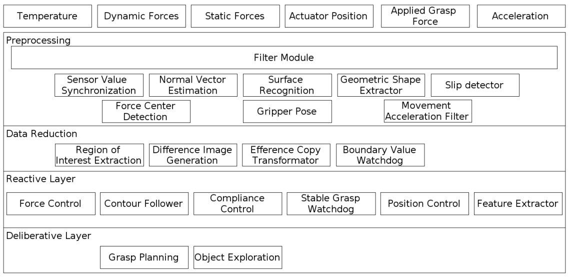

Figure 7: Proposed processing architecture for the gripper system

Fusioning of sensor information is necessary to get reliable sensor information. The movement acceleration filter for instance uses the force information from the tactile sensory system and combines it with acceleration sensor values from an inertial measurement unit which is placed in the wrist of the gripper. Increasing force values which are a result of the inertia of the grasped object in the gripper due to a movement of the complete manipulator can be filtered using the acceleration information. The geometric properties of a grasped object can be decomposed into simple geometric structures by fusioning the sensor information from the tactile sensors of all limbs of the gripper. Together with the other sensor processing modules in this layer, the information is sent to the data reduction modules which realise the communication from the finger modules of the gripper system.

Several approaches for reducing the communication load will be realised. Similar to video compression techniques one solution for keeping the amount of data that needs to be send low is to compare the current sensor information with the previously sent and transfer only the changes of sensor information. If changes are expected to happen only in small areas of the sensor modules, region of interests could be set to reduce the data. In the same way boundary values could be defined which are used to monitor the sensor input. As long as these are in a certain range, no sensory data will be sent to higher layers. This approach could be used for temperature values at the gripper surface which is mainly used for self-protection reasons. In combination with a manipulator arm together with information from some visual sensors and the desired gripper pose the contact points of the gripper to a grasped object can be calculated and used to estimate the resulting sensory feedback. This approach which processes a copy of the motor control commands of the end-effectors is known as efference copy [37] from neuroscientific research and can be used to reduce the data that needs to be send to higher level processing layers.

The resulting information serves as input to the reactive layer of the control architecture which directly reacts on sensor stimuli like force- and position control or using the tactile information to follow a contour that has been recognized or ensuring that a stable grasp is warranted.

These modules are accessed by the components from the deliberative layer where grasp planning algorithms and object exploration strategies will be realised.

Advanced model based prediction approached can be realised in conjunction with a complete robotic system that is equipped with several other modalities to fulfill the requirements for such an architecture.

## 5. Feasibility of the described approaches

Within this paper we want to present the feasibility of the approaches that have not been used in deep-sea environments until now. Especially the tactile sensor principle which has been described among the approaches for realising a deep-sea fine-manipulation system is new to deep-sea applications The general functionality of the actuation system is discussed in [16]. The performance of the tactile sensory system at 600 bar ambient pressure will be described in this section.

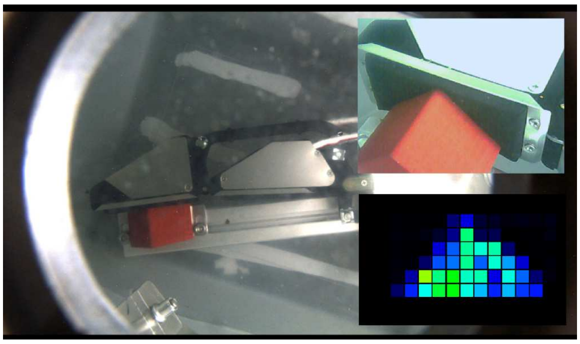

Figure 8: The sensor experiment in the pressure chamber at 600 bar

The experiments were conducted in the pressure chamber at the DFKI Robotics Innovation Center (RIC) Bremen. This pressure chamber is capable of generating ambient pressure of up to 600 bar. As this pressure chamber is equipped with connectors for hydraulics and electric, we are able to test our objects in-situ. Currently three monitoring cameras capture the experiments that are done in the pressure chamber.

For testing the tactile sensor, we integrated one of the finger modules that has been already designed in a setup where the end-effector is touching an object with a basic geometric shape that can be recognized from the tactile sensory data. The sensor field consists of 72 sensor elements, which are placed on an area of 6x3 cm. the whole setup is submersed in a box filled with silicone oil as it will be realised in the skin layer of the fully integrated gripper system.

Figure 8 shows the described experiment captured from the overview and gripper detail camera. The graphic in the lower right corner shows the tactile feedback at 600 bar ambient pressure. The sensor itself is covered with a black PVC sheet in order to avoid surrounding light to affect the sensor feedback of the gripper. The geometric structure of the touched object - which is a triangular shaped building brick - can be seen on the tactile image of the sensor.

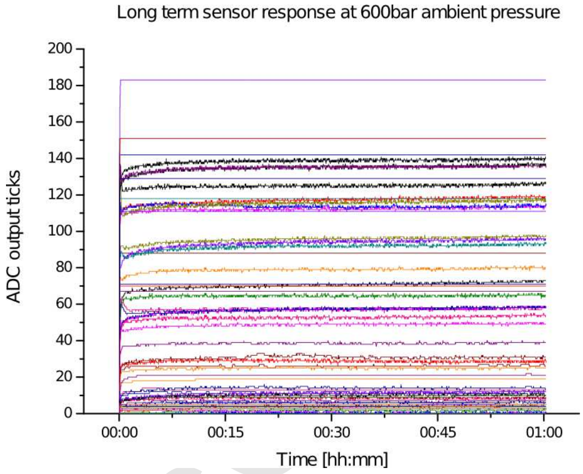

Figure 9: Long term sensor response of the tactile field

The long term raw sensory feedback for the sensor while touching the building brick at 600 bar is shown in figure 9. Creeping signals can be identified at the beginning of the experiment which might come due to relaxation effects in the cell structure of the foam due to displacement of the viscous oil. While some sensor elements do have a slightly noisy response others do respond with a stable sensory feedback. This observation can be explained with the different sensor offsets the sensor elements have due to unevenly distributed lighting conditions coming from the light induction as well as from the slightly inhomogeneous structure of the foam. Due to these effects, some of the sensors are already at the maximum output of the internal ADC of the camera which has 8 bit resolution. After reaching a stable state, good long-term stability of the single sensor elements can be observed which needs to be quantitatively measured in further experiments.

Figure 10 shows the averaged sensor response to repeated sensor activation by the building brick object. A deviation of 0.05 % on the averaged sensor feedback can be observed when measuring 30 seconds after the impact on the touched object .

## 6. Conclusions

Fine manipulation in deep-sea requires more delicate morphological setups compared to the two-limb structure of industrial deep-sea manipulation systems. Nonetheless, there has a tradeoff to be made between complexity and the ability to perform form-closure. By looking at the state-of-the art, it can be concluded, that none of the systems known today has been capable

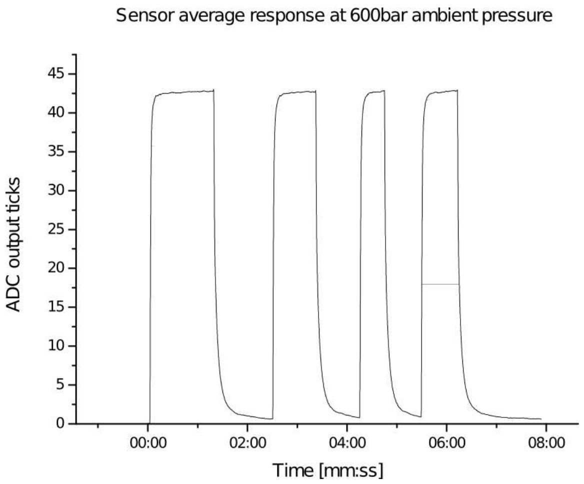

Figure 10: Repeatable sensor response of the tactile field

of reaching deep-sea environments of at least 1000 m depth. All the technologies required in order to design a multi-limb gripper system with tactile feedback for 6000 m depth have been presented and discussed. Most of these technologies have already proofed their deep-sea capability in various applications. The presented optical measurement system for detecting object geometries and pressure distribution has not been used in underwater scenarios before and thus is described intensively from the working principle and signal feedback. By looking at the sensor performance during the tests at 600bar ambient pressure, it can be concluded that this sensor system is suitable for deep-sea usage. Currently, this system is implemented by following the made decisions described in this paper. As soon as the system is ready, the system can be evaluated under real world application scenarios together with high-level object recognition algorithms using tactile feedback.

## 7. Acknowledgements

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**Peter Kampmann** studied Computer Science at the University of Oldenburg. He received his M.Sc. degree in 2008. He is currently working in the area of underwater and space robotics at the German Research Center for Artificial Intelligence. His research interests are tactile sensors, signal processing and embedded systems.

**Frank Kirchner** is the director of the Robotics Innovation Center and speaker of the Bremen location of the German Center for Artificial Intelligence (DFKI). He obtained a Dr. rer. nat. in Computer Science from the University of Bonn and was appointed a 'Full Professor-C4' at the University of Bremen, heading now the Chair of Robotics. He is in charge of a series of national German and US American projects focusing on autonomous intelligent robots in real-world applications. His fields of activity include application-oriented basic research on technology development and application of intelligent robotic systems and machine learning.