Equipping industrial deep-sea manipulators with a sense of touch

Peter Kampmann*, Timo Stoffregen* and Frank Kirchner*,†
*German Research Center for Artificial Intelligence
Robert-Hooke-Str. 1
28359 Bremen, Germany
†University of Bremen
Robotics Group
Robert-Hooke-Str. 1
28359 Bremen, Germany

***Abstract*—Tactile manipulation underwater is a topic still mainly bound to research applications. To change the situation, a drop-in replacement for the jaw gripper of an industrial deep-sea manipulator is developed that is equipped with tactile sensing elements. Special focus has been paid to the robustness of the tactile sensing elements, so that it might operate under the harsh environmental conditions during offshore operations. This paper discusses the system design and the sensor performance of the developed gripper module.**

I. Introduction

Most underwater manipulation tasks performed with ROVs are controlled using visual feedback, supplied by cameras which monitor the operational area. Increasing the range of sensor feedback from the operational area is desirable for ROV operators, especially as the impression of distance is missing from visual non-stereoscopic feedback. Several developments in the last years have been dealing with supporting operators by computer assistance [1] or by the development of dexterous manipulation systems with tactile feedback [2], [3], [4] and [5]. However, these developments aim at realizing new types of endeffectors for deep-sea manipulation.

The goal of the work presented here is to bridge the gap between dexterous underwater grippers with tactile sensors and the traditional jaw grippers found on industrial deep-sea manipulators. A jaw gripper module is developed that is able to support manipulation tasks with a sense of touch in the claw of industrial manipulators for deepsea environments (see Fig. 1). Research into this direction has been reported by [6], where a piezoelectric sensor element feedback was integrated in the jaw gripper to generate a vibro-tactile feedback to the operator. Within the work peresented here, a pair of gripper jaws have been developed that resemble the original structure of the end-effector of the Orion 7P deep-sea manipulator from Schilling Robotics. Based on previous experience on tactile sensors for deepsea applications [7], these gripper jaws have been equipped with two different tactile measurement principles. The tactile elements have been embedded in the structures which enable the manipulation of T-bar handles as well as force-closure grasps. Both approaches function independently from the pressure induced by the ambient water column. Special efforts have been taken to integrate of the tactile sensors in a way that secure the sensors from sharp object contact or large strain.

A detailed overview on the design is given in the following section. Experimental results in water of differing turbidity are shown that validate the chosen concept. The paper concludes with the lessons learned and an outlook on further developments.

Fig. 1: Front and side view on the developed parallel jaw gripper modules with tactile sensing elements

II. Design

While there are many ways of implementing touch sensors [8], a measurement system needed to be implemented in which the measuring electronics could be protected from the sensor interface, since this would be exposed to up to 600 Bar water pressure. Two sensor types stood out as being especially suited to this particular application, one based on a previously developed sensor based on a fiber optic measurement principle [9], the other based on the proximity measurement of fixed magnets. Both of these sensor types were implemented, the fiber optic measurement sensor requiring only the tips of the fiber optic cables to be exposed to water, the magnetic sensor requiring only fixed magnets being exposed to water. A further issue with using tactile sensors in high pressure aqueous environments is preventing the water column from depressing the sensor. This is prevented in both sensor types by flooding the sensor interface, hence equalizing the pressure.

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Since the geometry of the jaw modules was to follow that of the original as closely as possible, several constraints were considered regarding the design of the jaws. Specifically, the mounting flange and the gripping surface needed to remain unchanged, the bottom surface corresponding to a standardized T-Bar tool set. The resolution implemented in the jaws was 76 tactile points over an area of 4600 mm^2, giving a spatial resolution of 60 mm^2.

A titanium alloy of grade 5 (Ti-6Al-4V) was chosen for the jaws since this material has excellent properties regarding strength and corrosion resistance and is hence often used in marine applications. Further, this alloy lends itself well to precision wax-casting techniques. However the material used in the prototype jaw was *Polyamide Duraform* via SLS.

Waterproofing of the on-board sensing electronics was facilitated by flooding the internal cavities with epoxy resin using a pressure tolerant design concept [10]. This eliminated the need for seals whilst relieving the structure of load by compensating external pressure. This was the only part of the jaw which was waterproofed, the region between the components four and five in Fig 2 being left open to external fluids in order to equalize water pressure.

A. Structural Design

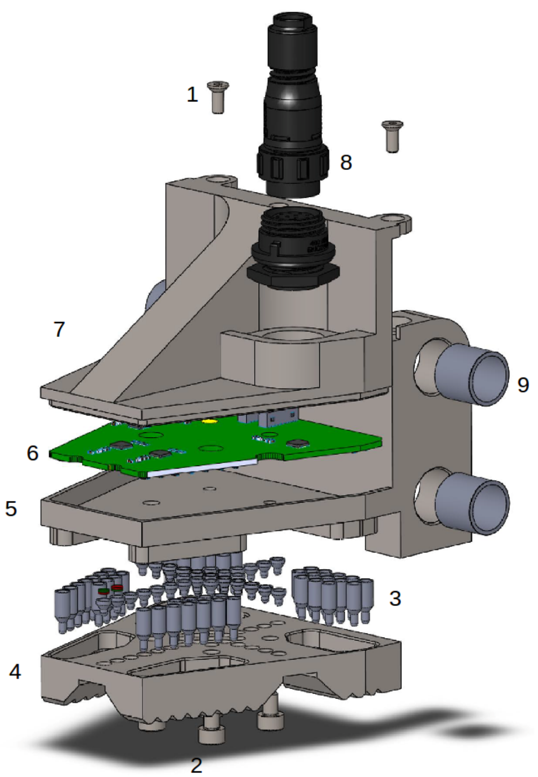


Fig. 2: Exploded view of jaw structure. 1,2 bolts, 3 push rods, 4 gripping surface, 5 jaw case, 6 Hall sensor array PCB, 7 lid, 8 Buccaneer-400 plug and socket

While two grippers were designed, they differed only slightly in their structure. The sensing electronics are placed within a pressure tolerant, waterproofed housing. External forces are transmitted via push rods within the sensor pad (compare Fig. 3), so that the sensor interfaces do not have to come into direct contact with potentially destructive forces. Hence, a cavity had to be created with respect to the original jaw in order to house the sensing electronics and a sensor pad integrated to house the push-rods. These were designed to have a stroke of 2 mm.

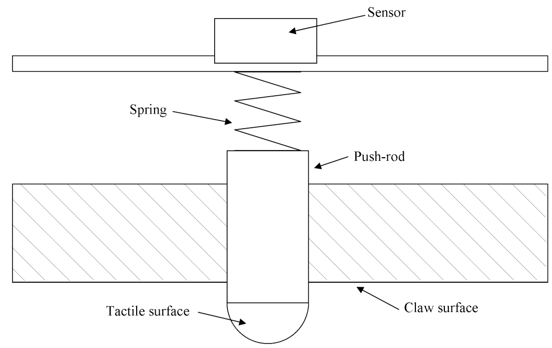


Fig. 3: Cross section schematic of structure.

B. Sensor Development

1) Optical Sensor: The optical measurement sensor implemented is operated by emitting light via an optical fiber into an an isotropic scattering medium, here a 4 mm thick semitransparent porous elastomer (see Figure 4). Some of the scattered light enters a second optical fiber which runs to a CCD sensor capable of measuring the light intensity. Since the intensity of the captured light is proportional to the thickness of the elastomer, compression of the elastomer by externally applied forces allows the inference of the strength of these forces.

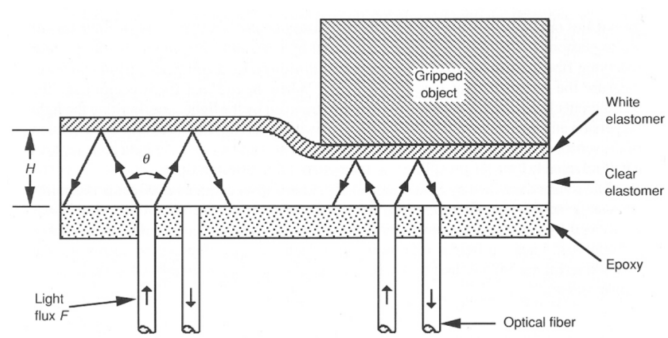


Fig. 4: Working principle of the optical contact measurement principle [11]

The optical fibers carries the scattered light to modified camera modules, whose output image is processed by a previously developed FPGA board (see [7] for further details). The contact information of the sensor elements is extracted from the obtained camera image as it is shown in figure 5. Five optical fibers with 0.25 mm diameter are allocated to each taxel and placed on different camera sensors in order to create redundancy in the case of failure. The isotropic foam, originally 4 mm thick is pre-compressed in a 2 mm wide cavity in order to operate in the linear responding range of the sensor. The stroke of the push-rods at the contact region is designed to never fully compress the foam material. This approach ensures the intactness of the foam even with sharp objects at the contact location.

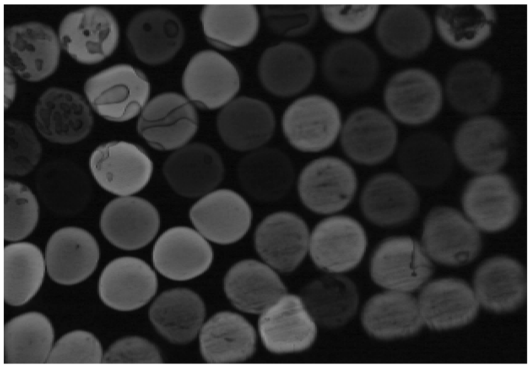


Fig. 5: View of the optical fiber bundle attached to the CCD sensor

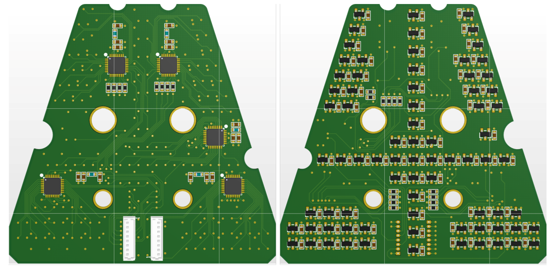


Fig. 6: PCB with Hall effect sensor array

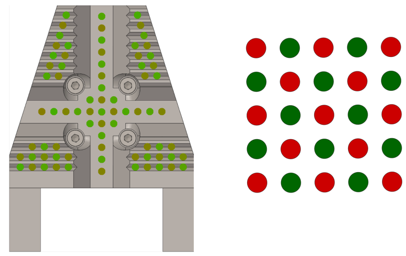


Fig. 7: *Right*:Fixed magnets are placed in alternating polarity (red = North pole, green = South pole) *Left*: The effect of the alternating array of magnets on the sensor (quiescent). The difference between values is 120.

2) Magnetic Sensor: The magnetic sensor is operated by measuring the proximity of a fixed magnet attached to the push-rods and a Hall effect sensor. A PCB with a array of 76 *Allegro A1301* Hall effect sensors was designed to this purpose. The output of these sensors is captured by an *ATMega328* microcontroller. Since the microcontroller only has five ADC pins, the output of the Hall effect sensors is switched between five 16-bit multiplexors. Low-pass RC filters with a cutoff frequency $f_c = 10$ Hz are placed in front of the ADCs in order to remove external electromagnetic noise.
Since the magnetic sensor is likely to be affected by external magnetic fields, both static and oscillating, some further means were introduced to remove such interference. In particular the removal of static magnetic fields proved to be challenging. For one, a reference Hall effect sensor was placed on the board for the detection of external magnetic fields. The magnitude of any such detected fields is directly added or subtracted to the output of any sensors in the vicinity. A further strategy to recognize static magnetic fields is placing the magnets in alternating polarity. Hence one sensor recognizes an external force by detecting a negative magnetic field, whilst its neighbor recognizes positive magnetic fields. The introduction of an external magnetic field thus produces a characteristic pattern by which all sensors become either more positive or more negative, a situation that was unlikely to arise from anything other than an external magnetic field. The magnitude of the external magnetic field is determined by inspecting a list of previous derivatives of sensor values. However this approach is prone to not correctly recognizing static magnetic fields slowly introduced to the sensor array. A better approach is to place the Hall effect sensors in alternating polarity rather than the magnets, since the magnitude of external magnetic fields is then be recognized without the need for calculating derivatives.

III. Experimental Results

Experiments on both end-effector designs were carried out to evaluate the performance and to identify potential weaknesses of the chosen measurement principles. Turbid water conditions are a potential threat to the fiber-optic measurement principle, since the chosen foamy material that is in contact with water is prone to contamination, hence altering the light scattering properties of the foam and therefore sensor performance. Tthe effects of turbidity were thus evaluated to identify potential changes in the sensor feedback.

A. Effects of turbidity

Due to the open design of the jaw module water is able to float within the force transducing area of the jaw module. The jaw module that uses the optical measurement principle has the potential to be influenced by turbid water conditions. To evaluate the effects of the sensor feedback, the sensor elements of the jaw module were activated in water under conditions of varying turbidity. The experiment setup consists of a basin filled with water and a digital turbiditymeter. By adding clay powder to the water, the turbidity is changed. Figure 8 shows the results for a sensor element of the jaw module.

The initial turbidity in tap water was recorded to be at 10 FTU. During the experiment a drop by 28 % in dynamic range and a loss of 45 % of the initial sensor offset was observed.

By washing or replacing the contaminated foam of the sensor, the dynamic range can be restored. The design of the jaw allows the replacement of the foam with low effort. To replace the foam, four bolts (position 2 in Figure 2) have to be opened.

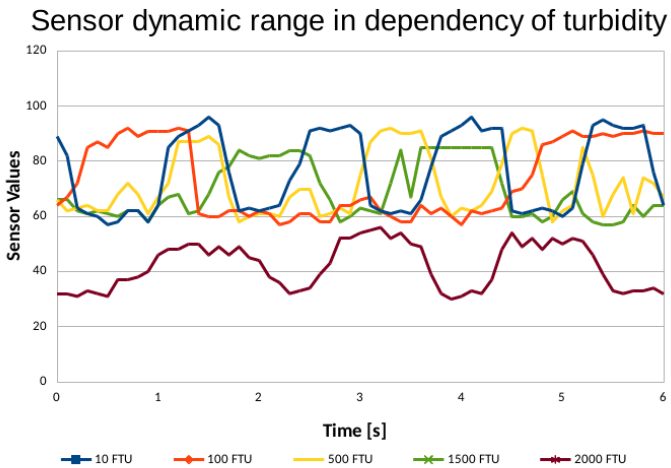


Fig. 8: Effects on turbidity on the dynamic response of the sensor

B. *Effects of surrounding magnetic parts*

Magnetic parts or generated electromagnetic fields are potential disturbances of the jaw module working with Hall effect sensor arrays. The performance of the developed precautions to these effects as described in section II-B2 were evaluated by applying a magnetic field near to the contact surface.

The experimental setup consists of a magnet made of neodymium (12 x 5 x 18 mm, grade N42) that is placed at various heights above the gripper module. Figure 9 shows the sensor feedback from the jaw module in the presence of the magnet 35 mm above the sensor in the center of the contact area.

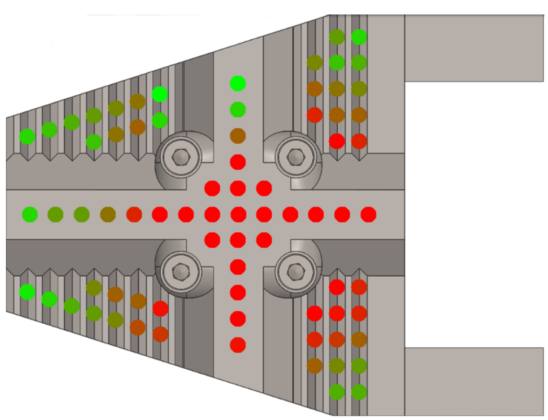
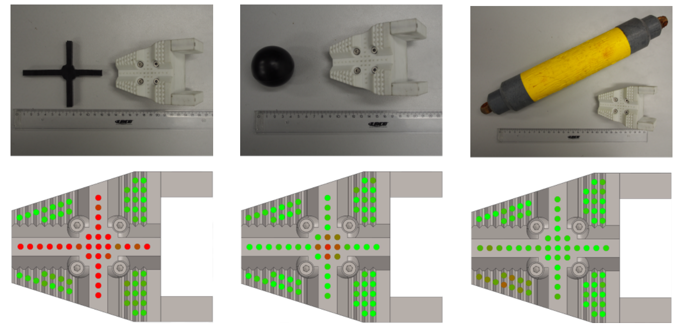


Fig. 9: Signal feedback from Hall effect sensors in the gripper in presence of a neodymium magnet 35 mm above the gripper

The sensor signal shows a strong response towards this magnet, which is an undesired feedback, as no touch contact has occurred on the sensor surface. The signal shown can be compensated to some extend by additional Hall effect sensors which are included in the design for reference as discussed in section II-B2. As compensation by the reference sensor is achieved by subtracting the offset that is introduced by surrounding magnetic fields, this approach can only work until the sensor becomes saturated. With the current experimental setup, the sensors reach saturation at a distance of 10 mm.



(a) T-bar handle (b) Sphere (c) Transponder

Fig. 10: Tactile feedback from the jaw modules grasping objects of different shape

C. *Sensor feedback for different objects*

The resulting tactile feedback produced by creating contact between the sensor surface and objects of various shapes is shown for the jaw module using the Hall effect sensor jaw in Figure 10.

With the given spatial resolution of the sensor elements, the tactile feedback of the two test objects reflects the situation at the contact area. The detection of contact through the tactile sensing elements has its limitations in the spatial resolution. Grasping the transponder mock-up shown in Figure 10c gives only little tactile feedback. Figure 11 shows contact area while grasping the transponder mock-up in more detail.

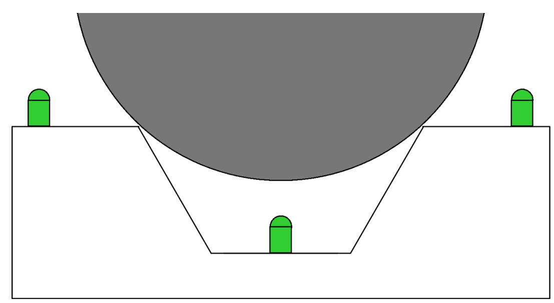


Fig. 11: Close-up view at the contact area while grasping the transponder mockup

As can be seen, the dimensions of the transponder object and the placement of the tactile sensor elements can lead to situations in which none of the sensor elements are activated during grasping.

IV. Conclusion and Outlook

The goal of the work presented here is to close the gap between dexterous underwater gripper using tactile feedback and industrial jaw grippers without tactile sensing. The chosen structural design relies on the original gripper structure and fixtures of a standard manipulator arm. Special focus has been paid on housing the tactile sensors for rough applications and environments.

Two measurement principles have been evaluated which by their working principle are able to operate independent from the water column. Both sensor types have their advantages and disadvantages in certain situations. While the fiber-optic measurement principle looses about 30 % of its dynamic range when exposed to strong turbidity, the Hall effect based measurement is sensitive to magnetic fields at the contact area. Selecting the optimal operating principle depends on the application scenario, a combination of both approaches towards a multi-modal setup increases the robustness but requires higher integration efforts.

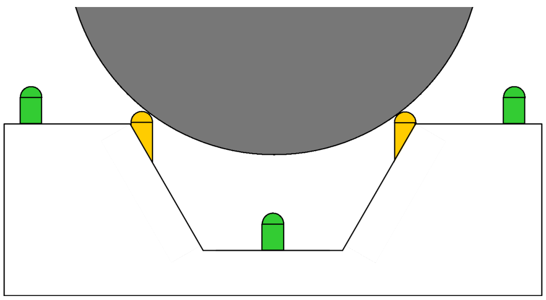


Fig. 12: Additional tactile sensing elements to recognize object contact of cylindrical objects

By grasping objects of different shape, it is shown that with the current setup of tactile sensing elements, situations occur where grasped objects do not generate a sensor feedback. In a further iteration of the concept, additional tactile elements are foreseen at the slope of the contact area as shown in Figure 12.

Further steps involve the incorporation of piezoelectric sensing material at the contact location as proposed in [7] to detect slipping objects effectively. Until now, the user feedback is limited to visualizations of the contact locations. Providing haptic feedback to the operator by using a force feedback device as shown in Figure 13 can increase the immersion of the operator to the operational area which is expected to facilitate the manipulation task.

Fig. 13: Haptic feedback of grasped objects

The current design requires cabling for data and power transmission from the jaw modules to a processing unit to be running along the manipulator arm. This limits the operating range of the end-effector on the industrial manipulator, as it is able to rotate in 360 °in the original configuration. Solutions, that maintain the degree of freedom like using optical rotary transmission [12] are options to look at.

Acknowledgment

This work has been funded by the German Federal Ministry of Economics and Technology (BMWi), project TransTerrA (grant No. 50RA1301).

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