Equipping industrial deep-sea manipulators with a sense of touch

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***Abstract*—Tactile manipulation underwater is a topic that is still mainly implemented in research. 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 on the robustness of the tactile sensing elements to operate under the harsh environmental conditions during offshore operations. This paper discusses the system design and the sensor performance of the deveveloped gripper module.**

I. Introduction

Most underwater manipulation tasks performed with ROVs are controlled using visual feedback coming from cameras that monitor the operational area. Increasing the feedback from the operational area is desirable for ROV operators as especially 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]. 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. 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 [5], these gripper jaws have been equipped with two different tactile measurement principles in the structure supporting the manipulation with T-bar handles as well as force-closure grasps. Both approaches work independent 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 different turbidity are shown that validate the chosen concept. The paper concludes with the lessons learned and an outlook on further developments.

II. Design

While there are many ways of implementing touch sensors [6], 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 [7], 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.

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.

The material chosen for the jaw was Ti-6Al-4V 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 [8]. 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 fig 1.4 and fig 1.5 being left open to external fluids in order to equalize water pressure.

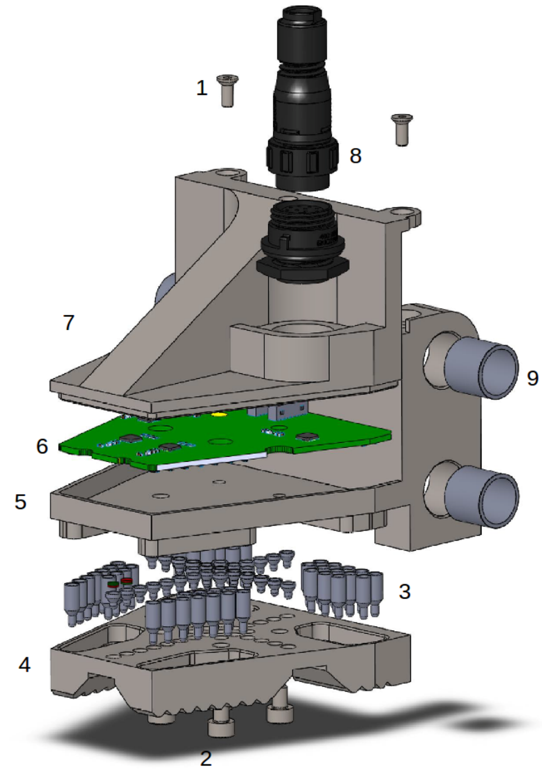


Fig. 1: Exploded view of jaw structure. 1,2 bolts, 3 push rods, 4 gripping surface, 5 jaw case, 6 Hall sensor array PCB, 7 lid, 8 Buccaneer-400 plug and socket

A. Structural Design

While two grippers were designed, they differed only slightly in their structure. The sensing electronics were placed within a protective, waterproofed housing. External forces were transmitted via push rods within the sensor pad, so that the sensor interfaces did 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. In the case of the optical sensor, significantly more space had to be created in order to guarantee a minimum bend radius of 4 mm for the optical fibers.

B. Sensor Development

1) Optical Sensor: The optical measurement sensor implemented operated by emitting light via an optical fiber into an an isotropic scattering medium, here a 4 mm thick semitransparent porous elastomer. Some of the scattered light entered a second optical fiber which ran to a CCD sensor capable of measuring the light intensity. Since the intensity of the captured light was proportional to the thickness of the elastomer, compression of the elastomer by externally applied forces allowed the inference of the strength of these forces.
The optical fibers carried the scattered light to modified webcam sensors, whose output image was processed by a previously developed FPGA board (see [5] for further details).

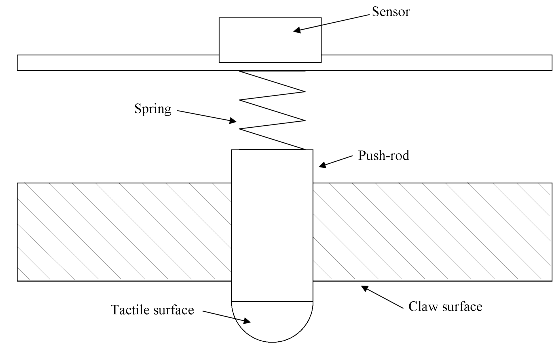


Fig. 2: Cross section schematic of structure.

Five optical fibers with 0.25 mm diameter were 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 was pre-compressed in a 2 mm wide cavity.

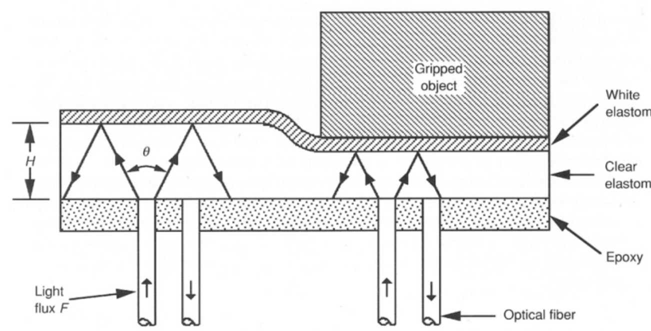


Fig. 3: Working principle of Kinotex sensor [9]

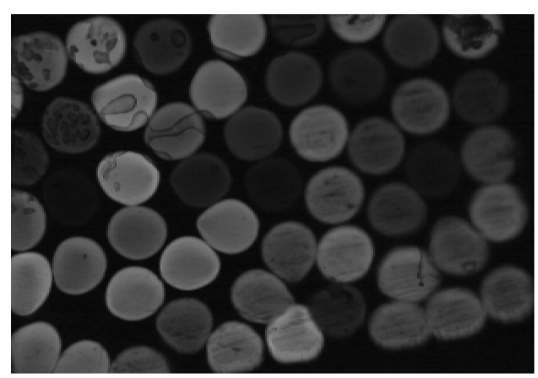


Fig. 4: View of the optical fiber bundle attached to the CCD sensor

2) Magnetic Sensor: The magnetic sensor operated by measuring the proximity of a fixed magnet attached to the push-rods to 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 was captured by an *ATMega328* microcontroller. Since the microcontroller only had five ADC pins, the output of the Hall effect sensors was switched between five 16-bit multiplexors. Low-pass RC filters with a cutoff frequency $f_c = 10$ Hz were placed in front of the ADCs in order to remove external electromagnetic noise. Since the magnetic sensor was likely to be strongly 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 could be directly added or subtracted to the output of any sensors in the vicinity. A further strategy to recognizing static magnetic fields was placing the magnets in alternating polarity. Hence one sensor recognized an external force by detecting a negative magnetic field, whilst its neighbor recognized positive magnetic fields. The introduction of an external magnetic field thus produced a characteristic pattern by which all sensors became 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 was determined by inspecting a list of previous derivatives of sensor values. However this approach was prone to not correctly recognizing static magnetic fields slowly introduced to the sensor array. A better approach would have been to place the Hall effect sensors in alternating polarity rather than the magnets, since the magnitude of external magnetic fields could then be recognized without the need for calculating derivatives.

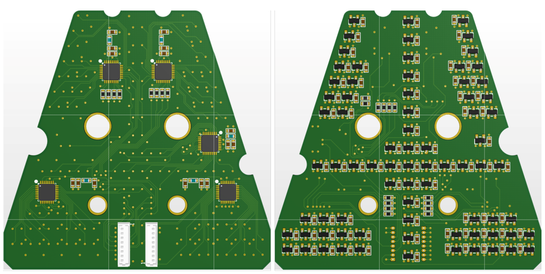


Fig. 5: PCB with Hall effect sensor array

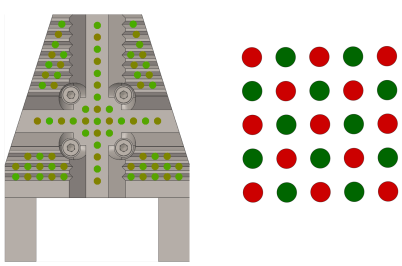


Fig. 6: *Right*:Fixed magnets are placed in alternating polarity (red = North pole, green = South pole) *Left*: The effect of the alternating array of magnets on the sensor (quiescent). The difference between values is 120.

III. Experimental Results

Experiments on both end-effector designs are carried out evaluate the performance and to identify potential weakness of the chosen approaches. Turbid water conditions are a potential threat to the fiber-optic measurement principle as the chosen foam material that is in contact with water is prone to contamination. Experiments on the effects of turbidity are there carried out to observe potential changes in the sensor feedback.

A. *Effects of turbidity*

Due to the open design of the jaw module that uses an optical measurement principle for detecting touch, the measurement principle has the potential to be influenced by turbid water coniditions. To evaluate the effects of the sensor feedback, the sensor elements of the jaw module have been activated under water with varying turbidity. The experiment setup consists of a basin filled with water and a digital turbid-itymeter. By adding clay powder to the water, the turbidity is changed. Figure 7 shows the results for a sensor element of the jaw module.

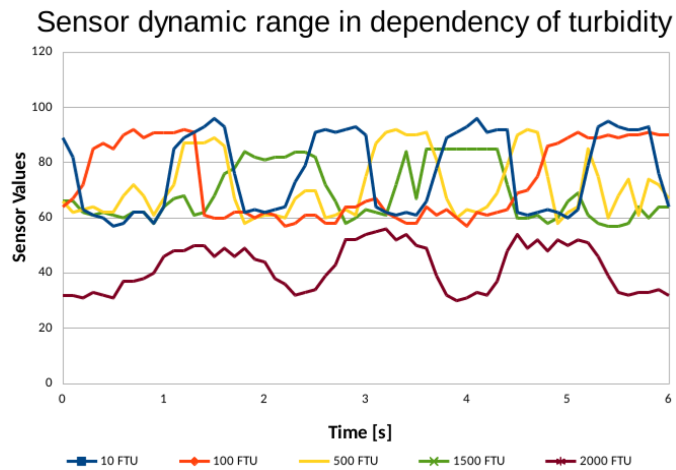


Fig. 7: Effects on turbidity on the dynamic response of the sensor

The initial tests of the sensor feedback in tap water are recorded at with a turbidty of 10 FTU. Over the experimental run, a drop by 28 % in dynamic range and a loss of 45 % of the initial sensor offset is 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 1) have to be opened.

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 are 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 8 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.

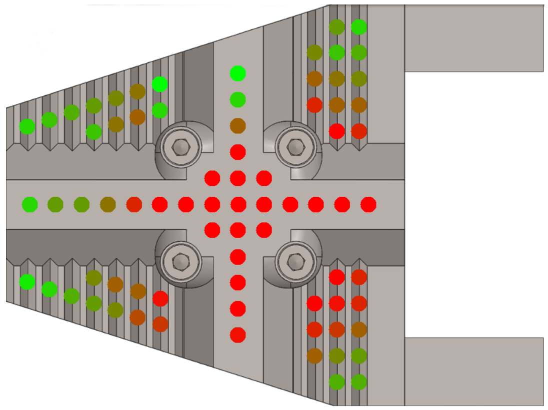


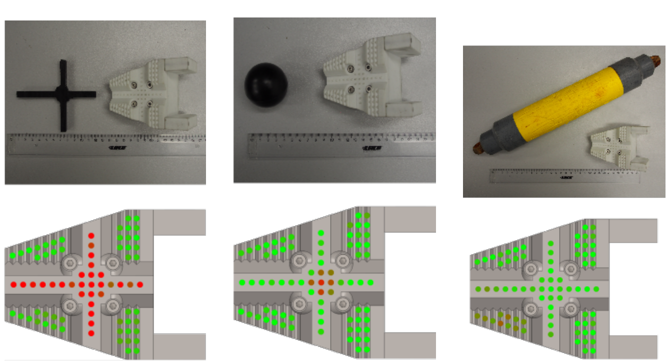
Fig. 8: Signal feedback from Hall effect sensors in the gripper in presence of a neodymium magnet 35 mm above the gripper

The sensor signal shows a strong response towards this magnet which is an undesired feedback, as not contact has ocurred. 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 works by substracting the offset, that is introduced by surrounding magnetic fields, this approach works until the sensor is saturated. With the current experimental setup, the sensors get saturated at a distance of 10 mm.

C. Sensorfeedback for different objects

The resulting tactile feedback while contacting sensing elements of different shape is shown for the jaw module using Hall effect sensors in figure 9.

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 mockup shown in figure 9c gives only little tactile feedback. This observation can be explained by the objects dimensions and the placement of the sensing elements at the contact area. Figure 10 shows contact area while grasping the transponder mockup in more detail.



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

Fig. 9: Tactile feedback from the jaw modules grasping objects of different shape

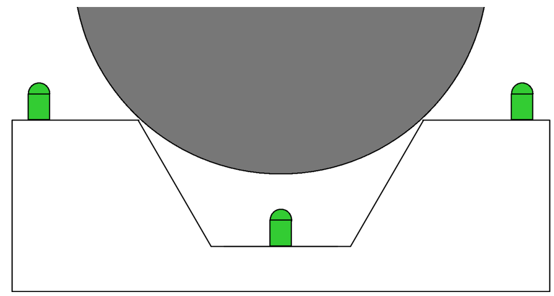


Fig. 10: Close-up view at the contact area while grasping the transponder mockup

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 is 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 design approaches take up the original gripper structure and fixtures of a standard manipulator arm. Special focus has been paid on housing the tactile sensors for rough application environments.

Two measurement principles have been evaluated which from 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 moving magnetic fields at the contact area. Selecting the optical choice from these measurement principles depends on the application scenario a combination of both approaches towards a multi-modal setup increases the robustness but requires higher integration efforts.

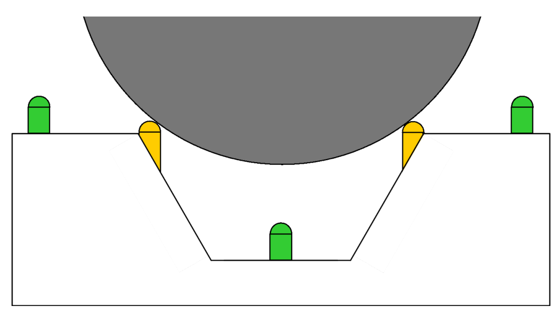


Fig. 11: Additional tactile sensing elements to recognize object contact of cylindrical objects

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 11.

Further steps involve the incorporation of piezoelectric sensing material at the contact location as it is proposed in [5] to detect slipping objects effectively. Until now, the user feedback is limited to visualisations of the contact locations. Providing haptic feedback to the operator by using a force feedback device as shown in figure 12 can increase the immersion of the operator to the operational area which is expected to facilitate the manipulation task.

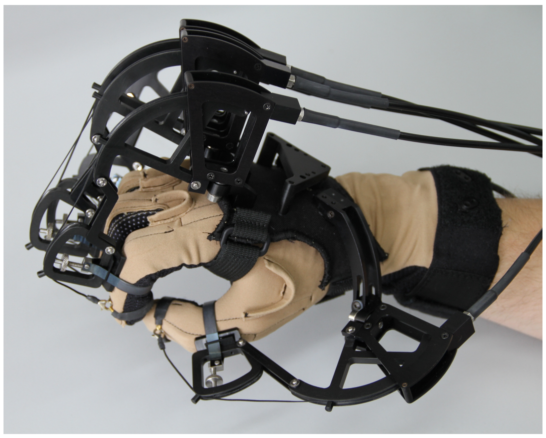


Fig. 12: Haptic feedback of grasped objects

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 [10] are options to look at.

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