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A Three-Fingered Cable-Driven Gripper for Underwater Applications

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Abstract— **In this paper, the design and experimental evaluation of a cable driven robotic gripper for underwater applications is presented. The gripper has three fingers and is characterised by a large workspace if compared with other similar devices reported in literature. Its kinematic configuration allows to execute both parallel and precision grasps on objects with very different dimensions. The gripper has 8 degrees of freedom actuated by only three motors by means of a suitable coupling of the joints obtained through the cable transmission. Moreover, in order to facilitate the execution of complex tasks, special force/torque sensors are mounted on the fingertips. The paper reports the main specifications deriving from the particular tasks in which the gripper is involved, and illustrates the proposed design solutions. Results obtained from real underwater experiments are provided as well, in order to demonstrate the capabilities of the gripper.**

Index Terms— **Robotic Gripper, Underwater Applications, Robust Grasp, Robotic Manipulation, AUV.**

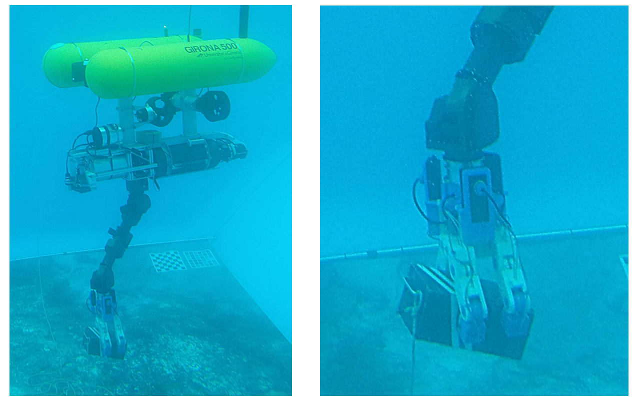

Fig. 1. The Girona 500 AUV platform with the redundant arm and the gripper operating in the CIRS (Centre d'Investigació en Robòtica Submarina of the University of Girona) pool: a dummy black box is recovered from the pool floor.

I. Introduction

In the next future, a rapid increase in underwater applications is expected for exploration, industrial activities and scientific purposes. Even if robots are already intensively used for undersea operations, actually they are remotely controlled by a human operator and they require a (usually big) surface vessel, making their usage very expensive. In this context, the availability of autonomous robotic platforms equipped with manipulation devices for the execution of grasping and manipulation activities will improve significantly the affordability of underwater robotic missions. In any case, for underwater robots intended to manipulate objects, the end-effectors are going to play an important role, as it is already the case in other contexts like industrial or space applications. The devices currently available on the market usually present a quite simple kinematics, a reduced dexterity, often limited to only one degree of freedom, and very limited or even absent sensorial equipment [1], [2]. Indeed, the limited variety of tasks to be executed so far in submarine activities did not really require a very "dexterous" device. On the other hand, the expected developments in the field, e.g. the introduction of automatic systems for assembly, inspection and intervention, will need more versatile end-effectors able to grasp and manipulate different objects in a very diversified way. In literature, few robotic end-effectors for underwater applications have been presented. The devices described in [3], [4], [5], [6] are among the few examples of systems for undersea grasping and manipulation purposes. Remarkable examples of grippers for underwater applications equipped with tactile sensors can be found in [7], [8]

In this paper, a three-fingered robotic gripper for underwater applications is presented. The main characteristics of this device are: 1) the transmission system based on cables routed through sheaths, allowing the arrangement of the actuators around the wrist both for reducing the distance between the palm and the wrist itself and for a better weight distribution; 2) the ability of grasping objects with very different shapes and dimensions with both parallel and precision grasp (fingers opposition); 3) the availability of force/torque sensors on the fingertip. This work has been developed as a part of the TRIDENT project, a research program supported by the European Commission and aiming at developing an autonomous system for submarine intervention activities, [9], [10]. The paper briefly reports also the results of the experimental evaluation of the autonomous underwater vehicle (AUV), developed within this project and equipped with a redundant arm and the gripper, see Fig. 1, as a demonstration of the effectiveness of the proposed device.

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II. General Design Specifications

During typical missions foreseen in the TRIDENT project, the AUV will autonomously explore wide underwater areas searching for a specified object to be recovered. Then, the intervention actions will be planned for retrieving the object(s), and non trivial manipulation activities will be performed. For these purposes, the currently available grippers have some limitations, deriving from the limited workspace, the limited type of achievable grasps (usually only parallel or enveloping grasps) and limited (or absent) sensory equipment, making it very difficult to achieve real autonomy in task execution. Therefore, a more versatile gripper has been designed within the TRIDENT project in order to provide the AUV with a more "dexterous" device, in such a way to ease the autonomous execution of (possibly) complex tasks. The main functional specification for the gripper are the following:

- the hand must be able to grasp objects with dimensions (diameter) in the range 5 ÷ 200 mm;
- the foreseen operating depth of the final project demonstration is about 25 m;
- the hand must be able to apply both force- and form-closure grasps with irreversible constraints;
- two- or three-finger precision, parallel and power grasps are desirable;
- local compliance on finger surfaces and/or actuation compliance is desirable in order to adapt to object shape irregularities, dimension uncertainties and stabilize the grasp;
- the sensory equipment of the hand should consider tactile sensors;
- the dimension should be kept as limited as possible, in order to have a low encumbrance of the arm/hand system during navigation.

In order to increase the manipulation capabilities of the AUV, the hand is installed on a 7 DoF, redundant arm. The arm has been designed with a modular approach, and is actuated by electric motors. For this reason, electric actuation is used also for the gripper. The communication between the control system, the motors and the sensors of both the arm and the gripper is implemented through a 2-wire CAN bus.

III. Design of the Gripper

According to the general specifications briefly summarized in Sec. II, the typology, in terms of size and shape, of objects to be grasped by the gripper may be quite large. On the other hand, it is not strictly required any internal manipulation capability, but rather the capability to firmly grasp an object. For these reasons, a solution composed by a mechanism with three fingers capable of a large workspace has been adopted. Moreover, almost all the mechanical parts are manufactured in ABS plastic for reducing the weight and increase the buoyancy, whereas anodized aluminum has been adopted for the metallic parts to prevent corrosion. The overall weight of the gripper is about 4.5 daN in air, while in water it is about 1 daN, that can be easily compensated by adding proper floats.

A. Kinematics

In Fig. 2 a schematic view of the gripper kinematics is reported. All the joints are of revolute type with PTFE bushings to reduce friction and prevent corrosion in marine environment. The gripper has three fingers: one named T (which can be intended as an opposable thumb), and two identical fingers named FR and FL (right and left finger respectively). This kinematic configuration is clearly inspired by the well known Barret Hand [11], that represents a suitable trade-off between hand functionality and design simplicity. The thumb has two links only: the proximal link, connected to the palm by a revolute joint (proximal joint) with a rotational axes parallel to the palm plane, and a distal link connected to the proximal link by a revolute joint (distal joint) whose rotational axes is also parallel to the palm plane. The FR and FL fingers differ from the thumb by the connection of the finger to the palm: in this case, an additional joint (palm joint) with rotational axis perpendicular to the palm plane is introduced between the palm and the proximal link, allowing the rotation of the whole finger with respect to the palm axis. This arrangement allows performing both parallel grasps as well as precision grasps, by means of opposition of the fingertips.

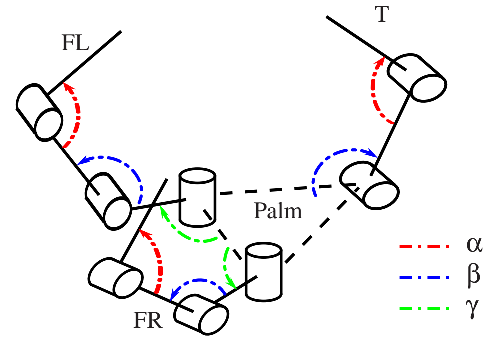
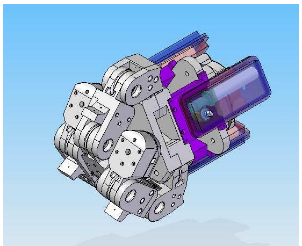


Fig. 2. Kinematic structure of the gripper.

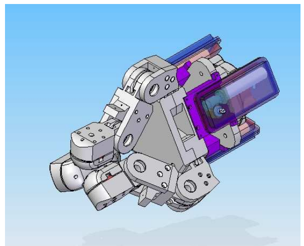
In total, the gripper has 8 joints, each one driven by an independent closed-loop cable actuation. On the basis of an analysis of the required gripper capabilities, and in order to reduce the overall weight, only 3 (identical) motors are used for the actuation. Obviously, couplings among the joints is present: these couplings are implemented in a very simple way by connecting in parallel the cable driving system of the three joint groups (i.e. distal, proximal and palm joints) to the same motor. With reference to Fig. 2, the angle $\alpha \in [90,\ 240]$ deg (distal joint angle) is actuated by a single motor for the three fingers at once, and the same applies to the angle $\beta \in [30,\ 180]$ deg (proximal joint angle) and the angle $\gamma \in [90,\ 150]$ deg (palm joint angle). The consequence is that, although only three motors are used, different configurations can be achieved, allowing a potential of many types of grasps on a great variety of objects, both in force and in form closure. Some significant finger postures and grasp configurations are reported in Fig. 3.

B. Actuation

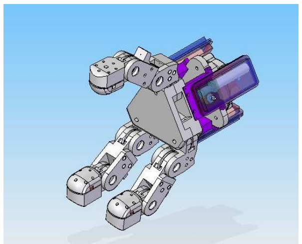
The actuation system of the gripper is based on the Faulhaber 12 W brushless DC motor EN 2250 BX4 CCD with integrated motion controller and CAN interface, provided with a 14:1 gearbox, guaranteeing a maximum torque of 1 Nm in continuous operation and of 1.54 Nm in intermittent operation. An additional worm gear 20:1 speed reducer is



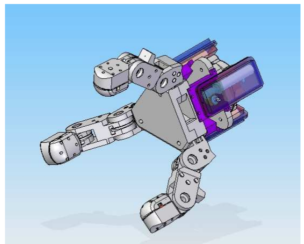
(a) Fully closed configuration.



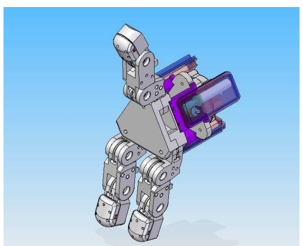
(b) Tripod precision grasp.



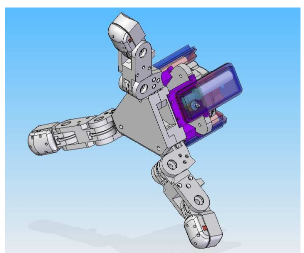
(c) Parallel grasp.



(d) Spherical grasp.



(e) Parallel opened configuration.



(f) Fully opened configuration.

Fig. 3. CAD view of the gripper design and kinematic configurations.

connected to the motor output shaft in order to obtain a proper torque/speed ratio between the motor and the load axis together with a more suitable arrangement of the motor for reducing the actuation encumbrance. Moreover, a reduction ratio of 4.6:1 is achieved by means of the different radii of the driving and the joint pulleys adopted in the cable transmission. Due to the gripper design, the main contribution to the normal fingertip force is given by the base joint. To compute the maximum fingertip normal force, we assume: 1) an equal distribution of the actuator torque between the base joints of the three fingers; 2) a distance between the finger base joint and the center of the fingertip of 170 mm; 3) a 20% torque loss due to friction along the cable transmission. It results that the maximum normal force applicable by each finger in continuous operation is about 150 N, which can be considered satisfactory for the typical operations of the TRIDENT project. Moreover, thanks to the introduction of the worm gear reducer, the actuators are non-backdrivable, a fact that allows holding the desired gripper configuration without further supplying power to the motors also during a grasp. The closed-loop cable transmission of the gripper, whose details are visible in Fig. 4, implements a double-acting actuator [12]. This transmission system has been adopted for several reasons:

- it allows to optimize the allocation of the motors in terms

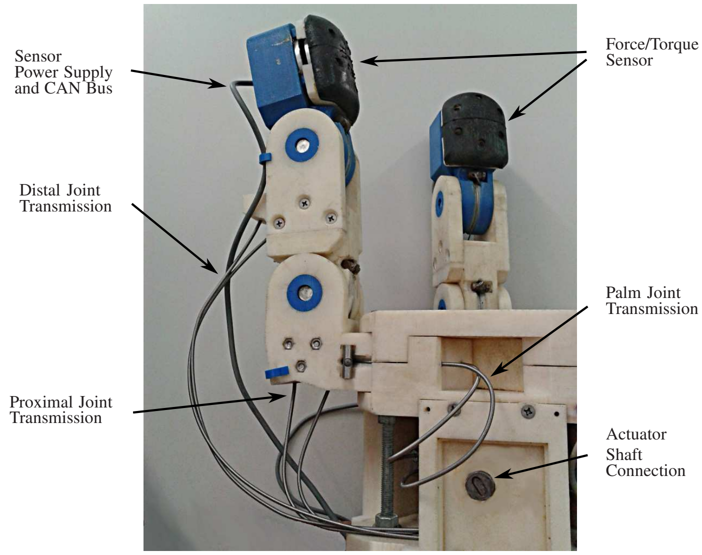


Fig. 4. Detailed view of the cable transmission system.

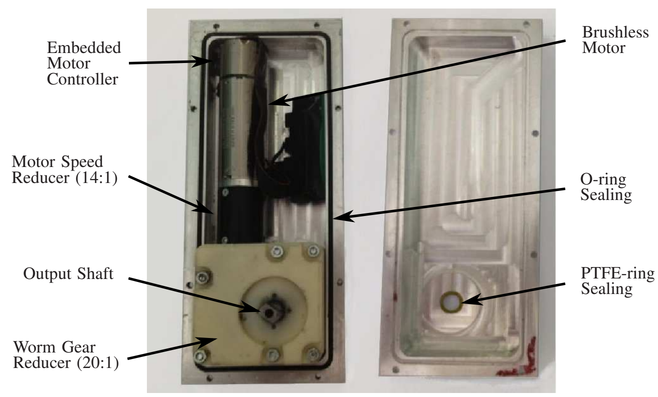
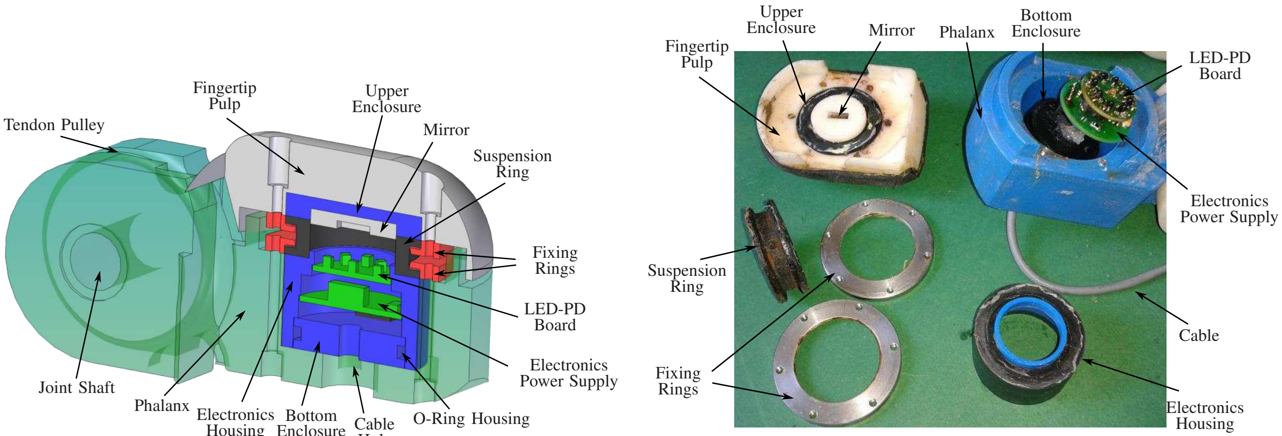


Fig. 5. Detail of the actuator and sealing parts.

  of required space and weight distribution;
- it represents a simple and convenient way to couple several joints to a single motor in a fixed way, so that the effective number of degrees of freedom is equal to the number of motors;
- it simplifies the transmission chain;
- the sheath-based routing introduces a small compliance in the transmission, allowing to prevent damages to actuators and speed reducers due to unexpected overloads.

The cable loop can be adjusted and preloaded by means of a suitable pretension mechanism (similar to the mechanism used in the bicycle brakes). The motor output shaft is connect to the cable driving pulley by means of a prismatic coupling, is such a way that the motor box can be detached from the cable transmission system (and the gripper structure) for repairing or maintenance without disassembling the cable transmission itself. The sealing system adopted for the actuators is very simple: each actuator, including the gear worm reducer, is enclosed in an aluminum box composed by two shells sealed by an o-ring, see Fig. 5, whereas the output shaft of the gear worm reducer is sealed by a couple of PTFE-rings



(a) Internal view of the fingertip force/torque sensor.

(b) The components of the fingertip force/torque sensor.

Fig. 6. Detailed view of the fingertip force/torque sensor.

for reducing the friction loss. Finally, a 4-wire cable carrying the 24 V power supply and the CAN bus is sealed by means of an epoxy resin for marine applications.

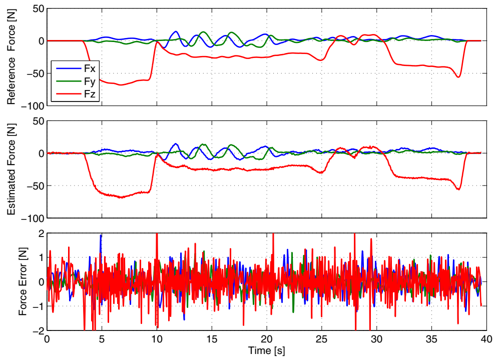
C. Fingertip Force/Torque Sensor

Specific force/torque sensors have been designed and implemented on each finger, see Fig. 6. In particular, the fingertip structure includes the sensitive parts of the sensor and its conditioning electronics, the data acquisition system and the CAN communication interface. The data acquisition and communication system has been implemented by means of a microcontroller that provides also filtering, scaling and conversion of the acquired data. Moreover, a rubber mold acts as a soft skin for the fingertip, increasing also the contact friction and the stability of the grasp [13]. The sensor is entirely enclosed in a plastic housing ensuring the sealing of the electronics. The working principle of the sensor adopted in the gripper is quite simple and has been already successfully adopted for other robotic applications, such as for the force and tactile sensors of the UB Hand IV anthropomorphic robot hand [14], [15]. The sensor is composed by 8 PhotoDetectors (PDs) mounted on a printed circuit board (PCB) and circularly arranged around an infrared light source (LED), and by a rectangular mirror facing the PCB and the optoelectronic components. The PCB is rigidly connected to the distal phalanx structure, whereas the mirror is connected to the fingertip contact surface. A deformable sealing ring, see Fig. 6(a), connects these two parts, allowing the relative motion of the fingertip contact surface with respect to the distal phalanx structure. The measurement principle of the sensor is based on the modulation of the current flowing through a PD generated by the variation of the relative position of the LED, and in particular of the angle of view between the optoelectronic components and the length of the optical path [16]. By means of this simple principle it is possible to detect the small changes of position/orientation of the rectangular mirror in any direction. The pose of the mirror can be then associated to the contact force/torque components applied to the fingertip surface by means of a suitable calibration procedure. In Fig. 7(a) and 7(b) a comparison of the forces/torques measured by the sensor and by a reference sensor (ATI Gamma SI-130-10) are respectively reported. The details about the model and the working principle of this sensor are not reported here for brevity, the interested reader can refer to [17], [18], [19] for a more detailed description of the sensing principle. It is important to note that the water pressure causes an offset on the force normal to the fingertip surface: this offset can be measured when the AUV reaches the desired working depth (before a contact occurs at the fingertips), registered by the control system and then subtracted from the measurement for a correct force estimation. In Fig. 6(b) the components of the fingertip force/torque sensors are shown in details.

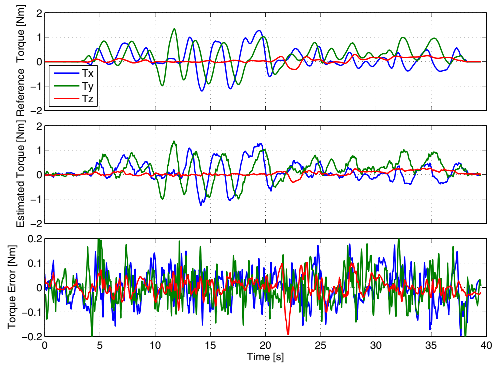
IV. The Arm-Gripper Control System

All the motors and the sensors of both the arm and the gripper share the same power supply and are interconnected via a standard CAN bus. A hierarchical structure has been adopted for the control of the whole system, composed by the AUV, the arm and the gripper. For both the arm and the gripper the low-level velocity/position control is directly implemented in the Faulhaber motor controllers. The Faulhaber motion controllers are commanded using the OpenCAN protocol [20] that allows basic functions such as monitoring of temperature and currents, velocity/position control, customization of the controller parameters and so on. The gripper force/torque sensors exploit the same CAN interface and protocol for data communication.

A middle-level controller is devoted to the coordination of the arm/gripper system with the AUV and is implemented, under the RTAI-Linux realtime operating system running on a PC-104 hosted on the vehicle, by means of a realtime task running at 100 hz. This controller communicates with the arm/gripper motors and sensors through the CAN interface (at 1 Mb/s) and calculates the set-point velocities of each joint in order to stabilize and hold the grasp at the desired shape on the basis of the kinematic model of the gripper and the force/torque fingertip sensors information. The middle-level

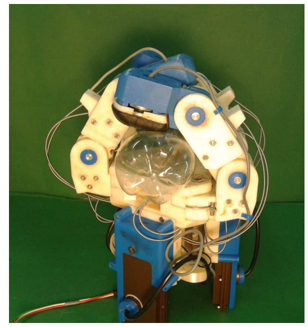


(a) Comparison of the estimated force with the reference sensor.

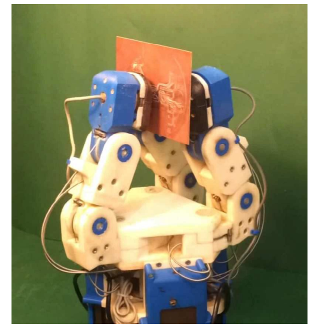


(b) Comparison of the estimated torque with the reference sensor.

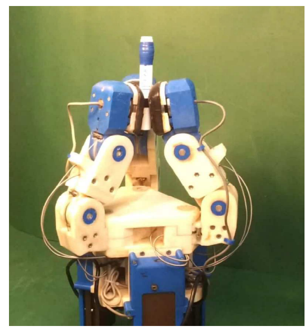
Fig. 7. Forces/torques given by means of the fingertip sensor.



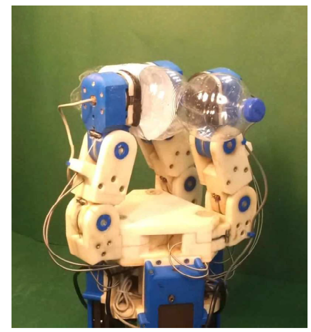
(a) Power grasp.



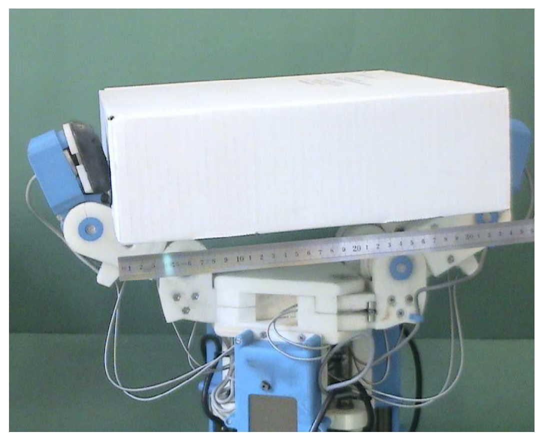
(b) Parallel grasp on a thin object.



(c) Pen tripod grasp.



(d) Parallel grasp on a plastic bottle.



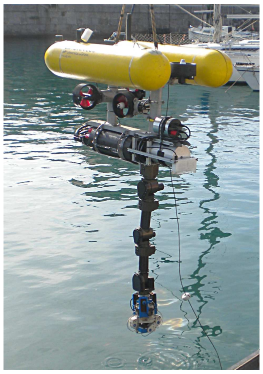
(e) The gripper grasping a 340mm width box.

Fig. 8. The gripper executing grasps on various objects.

controller receives also the commands from the high-level mission controller through an Ethernet connection.

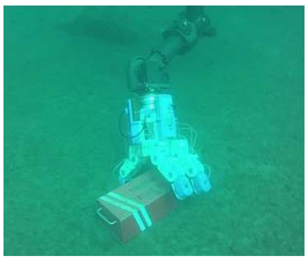
V. Experimental results

Preliminary experiments have been carried out in the laboratory to test the capabilities of the gripper. In Fig. 8 several grasps executed by the gripper are shown. The gripper is able to perform power grasps, see Fig. 8(a), to grasp different objects both in tripod configuration, as shown in Fig. 8(c), and in parallel configuration, see Fig. 8(b) and Fig. 8(d). In particular, Fig. 8(e) shows the ability of the gripper of grasping objects up to 340 mm width, whereas Fig. 8(b) shows the ability of grasping very thin objects. The whole integrated system composed by the gripper, the arm and the Girona 500 AUV [21], [22] has been then tested first in a pool available at CIRS (Centre d'Investigació en Robòtica Submarina of the University of Girona) as shown in Fig. 1. As a demonstration of more complex tasks, an experimental test in real undersea operations have been executed, according to the goals of the TRIDENT project. The AUV integrated with the arm/gripper system has been tested in the harbor at Port de Soller, Spain, operating at a working depth of about 25 m. Autonomous operations of the overall system have been successfully executed, as shown in Fig. 9 and in the video attached to this paper. The complete video showing the final experiments of the TRIDENT project is available at *http://www.irs.uji.es/2nd-i-auv/videos/E3-Autonomous-Intervention/TRIDENT-Final-Exp.mp4*. In particular, after getting the seafloor mosaic (generated on the survey phase), the AUV performed autonomous detection of the dummy black box to be recovered, and the grasp was specified by the human operator using a purposely designed user interface. Then, with the aid of the AUV vision system, the black box recovery stage was autonomously initiated by the system, as detailed in Fig. 9(d). For that purpose, a robust vision system has been implemented on the AUV by using both a 2D camera and a 3D vision system. Once the black box has been autonomously grasped by the gripper, the AUV brought it to the surface. The success of the experiment was observed thanks to the images provided by the onboard cameras of the AUV, and with the help of divers that recorded



(a) AUV deployment.

(b) AUV approaching the black box.



(c) The black box is approached.

(d) Grasp execution seen from the AUV camera.

Fig. 9. The AUV with integrated arm and gripper during the experimental tests at Port de Soller, Spain.

the experiment from outside, as shown in Fig. 9(b) and 9(c).

VI. Conclusions

In this paper, the design of a three-fingered cable driven robotic gripper for undersea activities has been presented. This gripper is characterized by a large workspace, and very different grasp configurations can be achieved thanks to its kinematics. Experimental data obtained in both laboratory and real tests have been briefly illustrated and commented on. The results show the positive aspects of the design choices, and, in particular, that the choice of the cable transmission system does not represent a limitation, but an advantage, even in the underwater environment. Particular attention has been devoted to the sealing system, focusing on the use of commercial components and on the reduction of the parts to be sealed for increasing the overall system reliability. The experiments carried out in the marine environment demonstrates the effectiveness of the mechanical design of the gripper, of its actuation systems and of the force/torque sensors purposely developed for underwater activities.

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