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Review

Underwater manipulators: A review

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ABSTRACT

This paper describes the state-of-the art in the area of underwater robot manipulator systems. A brief introduction is given on the use of manipulators in various offshore industries for different subsea intervention applications. It provides a comprehensive summary of existing commercial and prototype underwater manipulators, covering relevant aspects such as design features, their capabilities and merits, and provides a detailed comparison. This is followed by a thorough analysis of advantages and disadvantages of both electrically and hydraulically actuated manipulators. Furthermore, a detailed description of commercially available underwater manipulator control systems is presented in order to provide a realistic picture of the existing technology and its limitation. In addition, an extensive bibliography covering research results in the field of control algorithms is presented, including low level motion control, high level kinematic control and motion planning schemes along with the implementation issues.

1. Introduction

A manipulator (robot arm) is considered to be the most suitable tool for executing subsea intervention operations. Hence, unmanned underwater vehicles (UUVs) such as remotely operated vehicles (ROVs) and in some cases, autonomous underwater vehicles (AUVs) are equipped with one or more underwater manipulators. UUVs with manipulators are often called Underwater Vehicle Manipulator Systems (UVMS). The majority of existing underwater manipulators used on UUVs are anthropomorphic, i.e. they are designed to resemble a human arm. These manipulators are composed of a sequence of rigid bodies (links) interconnected by means of revolute joints with a suitable angular displacement between them and grippers or other interchangeable tools attached at the end-effector. For the observation of their surroundings they are usually accompanied with additional equipment comprising of one or more cameras and spotlights mounted on the base underwater vehicle and/or on the manipulator itself.

Underwater manipulators are used for a variety of subsea tasks in different applications within offshore oil and gas, marine renewable energy (MRE) and marine civil engineering industries as well as in marine science and military applications (Capocci et al., 2017). As they are being used in a wide range of applications, subsea manipulators are designed for different purposes, e.g. there are manipulators with limited mobility equipped with grippers for lifting large, heavy objects, manipulators used for fixing a detachable gripper to a selected, sunken object, grabber manipulators equipped with grippers or vacuum cups used to fix an underwater vehicle to submerged structures or near flat walls during the operation, manipulators equipped with inspection devices, dexterous intervention manipulators with grippers that can carry different tools used for repair and maintenance operations on submerged structures, etc. Usually, work class ROVs are equipped with two manipulators, in most cases one simple powerful grabber to hold the ROV near the hydro engineering structure or wreck, while the other manipulator performs the actual intervention task.

Some of the tasks underwater manipulators are designed to execute include pipe inspection (Christ and Wernli, 2014), salvage of sunken objects (Chang et al., 2004), mine disposal (Fletcher, 2000), cleaning surfaces (Davey et al., 1999), opening and closing valves, drilling, rope cutting (Christ and Wernli, 2014), cable laying and repair, clearing debris and fishing nets, biological (Jones, 2009) and geological sampling (Noé et al., 2006), archaeological work (Coleman et al., 2003), etc. In general, manipulators are located at the front side of the underwater vehicle, but this is not always the case, e.g there are vehicles with a manipulator located at the bottom side (Ribas et al., 2012).

A brief overview on underwater manipulators can be found in the underwater robots review paper by Yuh and West (2001). Antonelli (2014) provided a good theoretical background for underwater manipulators from the modeling and control point of view. However, a complete article encapsulating relevant practical and theoretical knowledge, state of the art technology as well as up to date research

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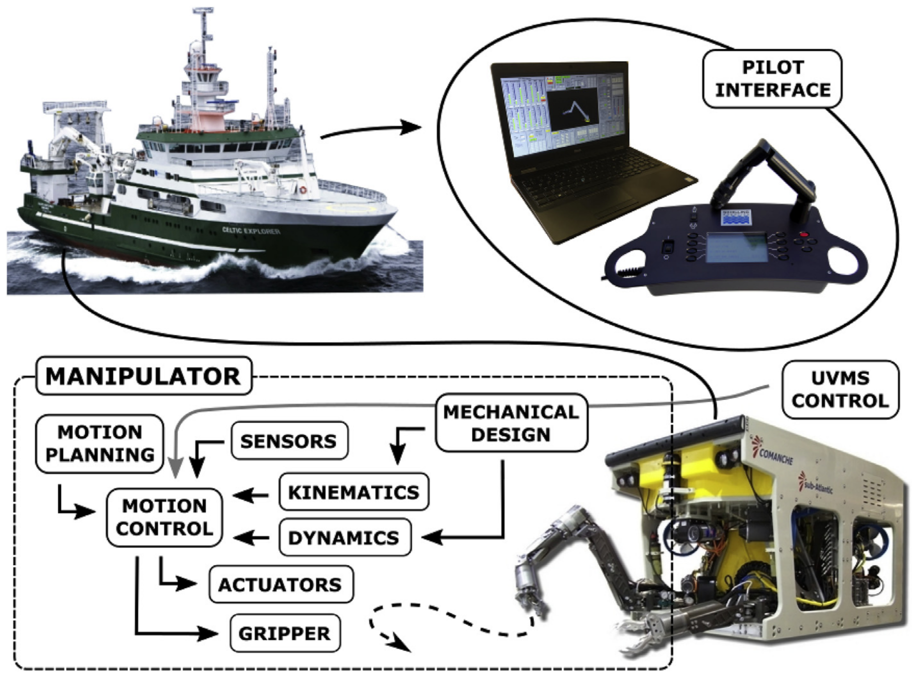

Fig. 1. Factors affecting underwater manipulator performance.

done in this area can not be found in the literature. Therefore, the aim of this paper is to provide a review of underwater manipulators covering all the relevant aspects, from an applied underwater research point of view. Fig. 1 outlines the factors governing performance for underwater manipulation, which are expanded upon in detail within this paper.

The remainder of the paper is organized as follows: Section 2 describes mechanical design features and capabilities of existing underwater manipulators and gives their comparison. Section 3 analyses underwater manipulator actuation methods. Section 4 describes control systems of commercially available subsea manipulators. Sections 5 and 6 cover academic research achievements in the area of motion control for underwater manipulators and underwater vehicle-manipulator systems respectively. The state of the art in kinematics control and motion planning algorithms is covered in section 7, while section 8 focuses on force control algorithms. Finally, Section 9 presents conclusion.

2. Mechanical design

In order to be able to operate in deep waters and cope with the harsh conditions of subsea environment, specialised materials are used in the construction of underwater manipulators. Additionally, depending on the task for which they are designed, underwater manipulators have to meet relevant requirements regarding the size of the workspace in which they are to operate, lifting capacity, wrist torque, etc. Table 1 lists specifications of existing commercial underwater manipulators.

The most common materials used in construction of underwater manipulators are metal alloys such as titanium Ti 6–4, anodized aluminium alloys (5083, 6082 T6, 6061 T6, 7075 T6, A356), stainless steel alloys (316, 630, 660), as well as some plastics (Polyethylene). The properties of these materials are relatively high strength and corrosion resistance and good machinability. To reduce the weight in the water and minimize the actuator burden, some experiments have been done on using buoyant materials on underwater manipulators (Ishimi et al., 1991). Typically, commercially available underwater manipulators are rated between 3000 and 6500 m of sea water (msw); however, some manipulators can operate in depths up to 7000 msw, e.g. Schilling Robotics Titan 4 and a prototype manipulator developed by Zhang et al. (2014). Additionaly, there are a some systems designed for full ocean depth (11000 msw). Woods Hole Oceanographic Institute in collaboration with Kraft Robotics designed one such manipulator for the purpose of Mariana Trench exploration mission (Bowen et al., 2008). Others include “Magnum 7”, a product of ISE Ltd. and, “The ARM” and “MK-37” developed by the Western Space and Marine, Inc.

The size of underwater manipulators is described by a parameter called “Reach” which represents the length of the whole manipulator kinematic chain. Along with the range of motion of joints, it determines the size of manipulator workspace, a set of points that can be reached by its end-effector (Cao et al., 2011). Reach of existing underwater manipulators ranges from 0.5 m for the grabber manipulators up to 2.4 m for heavy duty manipulators.

Maximum wrist torque which underwater manipulators are capable of producing ranges from 8Nm to 250Nm. According to ISO 13628–8:2002 (ISO 13628–8, 2002), rotary low torque ROV interfaces on subsea production systems, which are typically used on subsea tree needle valves, are rated to maximum 75Nm. Additionally, lifting/carrying (payload) capacity for underwater manipulators ranges from 5 kg up to 500 kg. Manufacturers often provide different parameters for manipulator lift capacity (“max. nominal”, “at full extension”, “at rated speed”, “through envelope”, etc.) which makes the comparison non-trivial as the carrying capacity is not a fixed value but depends on the pose of the manipulator.

Underwater manipulator weight (in air) is between 6 kg and 150 kg; however, their weight in water is more important, as it determines the buoyancy needed on the base vehicle in order to compensate for the manipulator. The weight and size are very important factors as they are directly responsible for the amount of dynamic coupling introduced between the manipulator and the underwater robot on which it is mounted and can thus influence the performance of the whole system. In order to be able to fully exploit manipulator characteristics, the manipulator weight should be a low enough percentage of the whole underwater robot weight, so that the dynamic coupling can be neglected or at least taken into account as an external disturbance that can be dealt with by the dynamic positioning of underwater robot (if this exists). Higher weight and bigger size bring about higher demands concerning the robustness of underwater robot thruster system to the disturbance caused by the dynamic coupling. In future research this