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Adaptable Joystick Control System for Underwater Remotely Operated Vehicles ⋆

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Abstract: Current commercial remotely operated vehicles (ROVs) used for inspection, maintenance and repair tasks of subsea petroleum facilities are operated with a low level of automation. Precise and efficient operation of the vehicles is hard, and the vehicle operators need extensive training to operate these efficiently. A properly designed automation system has the potential to lower the required skill and experience level for the operator, increase operation efficiency and counteract operator fatigue. This paper uses theory from development of human centered automation (HCA) in the aviation industry to propose a new human centered control system enabling shared control of ROVs.
The control system is implemented in a simulator and evaluated qualitatively. The human centered control system includes four modes of operation; position control, object of interest orbit control, autopilot mode, and waypoint guidance mode. The main contributions of this work are as follows: a human centered approach in ROV control system design, development of a reference velocity scaling for predictable position control, an adaptive joystick deadband function, an orbit control mode using a super-ellipse as base shape. Finally, guidelines for predictable control system behavior are suggested.

Keywords: Human Centered Design, Human Machine Interface, Remote Control, Unmanned Underwater Vehicle, Subsea, IMR

1. INTRODUCTION

Most inspection, maintenance and repair (IMR) operations on subsea petroleum extraction facilities are performed using remotely operated vehicles (ROV). Currently there are over 5000 subsea Xmas Trees installed on the seafloor of the world's oceans. All these need to be inspected and maintained yearly by ROVs. These are unmanned underwater vehicles controlled from a surface vessel through an umbilical cable. This class of vehicles has had a rapid development curve from the 1970s, when they were first introduced for work in the oil and gas industry. However commercial ROVs used today have not followed the development of other industries when it comes to automation (Offshore Engineer (2015)). ROVs are currently operated in a *direct control* mode. The operator uses a joystick to control forces produced by the ROV-propellers, and a master-arm is used for controlling the position of the manipulator arms (slave-arm). IMR operations often require at least two operators (ROV pilots). These pilots need extensible training to be able to control the ROV efficiently, and a persistent situational awareness is critical.

Introducing more automation in the ROV control system has the potential to relieve the operator from the tedious task of manual control during long operations. This will counteract operator fatigue and make the operator work faster with less training (Schjølberg and Utne, 2015).

The goal of the work is to introduce shared control for ROVs performing IMR operations, making the operations faster, safer and easier.

Yoerger et al. (1986) introduce the idea of relating joystick command to different reference frames and use this to propose different control modes. The work showed that performance is improved with a closed loop control system using shared or supervisory control. This evaluation was based on simulation with a pilot in the loop. This very early work did not consider human performance, and the conclusion was based on the track following capabilities of the control system. Dukan and Sørensen (2012) focused on methods for relating joystick commands to ROV motions and references. Three different schemes were proposed and experimentally tested. Two of the methods use a filtered joystick command as a velocity reference, one is integrated to a position reference and one is used directly. The third method relates the filtered joystick command directly to thrust forces on the ROV. The control system switches to position control when the velocity or thrust reference

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is zero. This is to keep the vehicle in a fixed position. Candeloro et al. (2015) takes an alternative approach to ROV-control by using a head mounted display with internal motion sensors to control an ROV.

This work develops a human in the loop (HITL) control system to be used for subsea IMR tasks. An ROV control system architecture for IMR operations is proposed. The architecture is developed using theory from HCA originating in the aviation industry. The different modes in the architecture include concepts from previous research. To investigate the usability, the control system was implemented in a simulator and tested with an operator in the loop. This testing was done in a qualitative manner with focus on user friendly operation of the ROV, and revealed weaknesses in the system. The presented work analyses these weaknesses, and proposes solutions for making the system more user friendly and robust.

The contributions in the presented work are to bring in theory from HCA from the aviation industry to ROV control system design. This is used as a basis for proposing design guidelines for the ROV control system. The theory and guidelines form the fundament for a new ROV control architecture with a higher level of automation than what exists in current commercial ROVs. The control architecture is novel and important as large cost savings are expected due to increased efficiency in IMR operations. Operator friendliness has been an important aspect in the design, and has led to the following contributions:

- A velocity scaling function to avoid joystick wind-up
- Adaptive joystick deadband for straight line manouvers
- An orbit control mode for inspection of subsea equipment with a rectangular footprint

This paper is organized as follows: Section 2 gives a short synopsis of HCA, and HITL control systems. Section 3 describes the different control modes and high level architecture of the control system. The control modes are presented in Section 4 and 5. Section 6 concludes the work.

2. GUIDELINES AND HUMAN IN THE LOOP

This section will give a synopsis of the concepts relevant for this work. Starting with a short introduction to HCA, and then an overview of the concept of having a human in the control loop, and distinguishing this from an automated feedback loop.

2.1 Guidelines for Design and Implementation

Designers of new automation systems often have a tendency to be too technology centered, trying to automate every part of the system (Norman, 1990; Sheridan, 2001). However, there are often tasks that are either too difficult or too expensive to automate. A human operator is therefore needed to monitor the system, to take over in case of an incident and to perform the tasks that are not automated. A more thoughtful approach to function allocation is the compensatory principle. In this approach, tasks are allocated to man or machine according to an assumption about who is best qualified to perform the task. This method originates from Fitts list (Fitts, 1951), which in spite of its age and criticism has persisted through history (Winter and Dodou, 2014).

Both the technology centered approach and function allocation tend to lead to problems in the human-machine relation, described as the *ironies of automation* in Bainbridge (1983). There is literature to be found on design principles of HCA, especially in the aviation domain. However, when it comes to functional design and implementation of a HITL motion control system there is a need for more tangible guidelines. Billings (1996) and Atoyan et al. (2006) provide guidelines for designing a HCA system. Such system can be viewed as a three piece system; the human operator, the automation system and the human-machine interface. HCA is a term often describing automation interacting with humans, where the goal is to optimize the overall performance of the system (Sheridan, 1995). This includes handling of both automation and human errors. Shared control is a similar term that most often is used to describe an automation system where the control is shared between an automation system and a human operator.

The presented work is focusing on the development of a control architecture supporting shared control for subsea IMR tasks. While many of the guidelines from the literature are related to training of the operator, and design of the human machine interface, the following four guidelines are addressing the ROV control system. These are proposed as the guidelines for designing the control system in the presented work (Billings, 1996; Atoyan et al., 2006).

1) The automated systems must be predictable
2) Provide the user with adaptable automation
3) The automated systems must also monitor the human operators
4) The automated system must be comprehensible to pilots

Guideline number two suggests that the operator can change the level of automation during mission execution. This switch between control modes must be intuitive and easy. To achieve this, the control system should be stable during a switch between control modes (guideline 1). A set of more detailed guidelines for predictable control system behavior during operation is proposed:

1a) The velocity and position references during switching should be continuous
1b) A command from the operator, should always lead to a vehicle response
1c) The same operator command should lead to similar response, despite of the current operating mode
1d) If a stop is commanded, the vehicle should stop as fast as possible, without reversing

2.2 Human in the Loop and Joystick Control

HITL control refers to the situation where a human is present in the control loop, fulfilling one or several control functions. The classic (closed) control loop consists of a controller and a process. The controller receives feedback from the process, and controls the actuators to drive it to the desired set-point. In ROV-control a human typically takes the place of the controller, and use video feedback from the vehicle to control the thrusters on the vehicle. A block diagram for such control loop can be seen in