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IFAC PapersOnLine 55-31 (2022) 118–123

Underwater Manipulator Control for Single Pilot ROV Control ⋆

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Abstract: Remotely operated vehicles (ROVs) are the main driver in inspection, maintenance, and repair (IMR) of underwater structures. The commercial use of ROVs in industrial applications dates to the 1980s, however, the control and operation of work class ROVs for performing IMR interventions still carried out by the team of minimum two expert ROV pilots, despite the immense efforts to automate the operation of ROVs in the last decades. This paper provides a new approach to automation of ROV operation by considering the needs of the ROV pilots. To this end, a new controller is presented enabling the subsea IMR operations with a presence of a single pilot. The results are tested using a residential work class ROVs in Snorre B (SNB) oilfield by an expert Pilot.

Keywords: Unmanned underwater vehicles, Remotely Operated Vehicle, Autonomous vehicles, Teleoperators, Robot control

1. INTRODUCTION

The earliest reference to tethered Remotely Operated Vehicle (ROV) dates back to 1953 when Dimitri Rebikoff converted his underwater scooter to the first ROV vehicle, the “Poodle”, allowing exploration of deeper parts of the ocean that were not accessible to humans. The poodle was basically a camera in a pressure-resistant housing equipped with water-corrected lens and mounted on a tether-controlled vehicle; see Christ and Wernli Sr (2013).

In the 1960s, United States Navy developed a concept that at the time was called “Cable-Controlled Underwater Recovery Vehicle”. The new development paved the way for ROVs to be the only viable solution for recovering underwater ordnance and torpedoes in deep seas. Soon, industry took the lead and only a few government owned ROVs in 1970s were increased to more than 3000 ROVs worldwide by 1998. These were mainly commercially owned.

These days, ROVs are used extensively in the oil and gas industry (O&G) and other underwater platforms for observation and intervention. Other applications outside of O&G include hydrographical surveys and cable laying.

Before diving into the technical aspects of the ROV and ROV operation, it is of utmost importance to highlight the fact that operation of ROVs these days is almost identical to 1970S: ROVs are operated by one or more operators or pilots. Despite all the advancement in automation of industrial ROVs, pilots still have the central role in operation of ROVs. It is worth to reflect a bit on why most of the automation developments in terms of autonomous operation of ROVs are not well received in the industry. First, we have to highlight that there exist no single degree or path to becoming an ROV pilot or operator. Some ROV pilot technicians have degrees in electrical, mechanical, or electronic engineering (but not all of them do). Some ROV Operators have military service qualifications with the appropriate levels of vocational qualifications. Different industrial ROV producers or industrial companies that rent out ROV operation services, offer their own training courses and certificates, however the content of such training varies substantially in different companies, and they are often tailored for specific type of ROV or specific operation. Even though the pilots acquire lots of training throughout their careers, they often build their own style of controlling the manipulator. Many ROV operations, especially offshore operations, requires availability of the pilot teams 24/7. It is a huge benefit if the control of the manipulators is more intuitive. An operator centric intuitive control of manipulators is the first step in reducing the number of pilots and moving toward a single pilot goal. This intuitive control methodology will also facilitate the possibility of swapping trained ROV pilots between different companies. This would allow the pilots who have worked with one specific type of ROV to easily adjust themselves to work with another type of ROV. This becomes even more important as many ROV control rooms are moving to onshore where a single shore control center offers service of operating many type of ROVs and operations.

⋆ This project is funded by IKM Subsea AS and the Norwegian Research Council through SMART-ROV project (project No. 313866).

10.1016/j.ifacol.2022.10.418

It was this circle of ideas that inspired us with development of the current article in which we propose a different strategy to provide the operator with tools enabling him to control the ROV alone. The implications of single pilot ROV control are huge for offshore industry because it could mean that two less operators are required for the job (one for each shift). This saves cost and cabin space on vessel. Also, one could argue that there could be a benefit in the efficiency of the operation because if there is one operator making the decision the operation can become smoother. This is because the operator knows best where he wants to position the ROV to reach what he is trying to manipulate (traditionally one pilot controls the ROV while the other controls the manipulator).

Despite little change in the ROV industry, there has been a great deal of research and development towards intervention AUVs and hybrid ROV-AUV systems. An excellent summary of these advancements are summarized by Petillot et al. (2019). The focus of this paper however is centered more towards reducing the manning of ROV operations. We fully agree that the ROV industry will change and move towards more autonomous operations. But this is a slow process and in the meantime, there are economic and environmental benefits to be had from reducing the manning of offshore operators. We have expanded on some of these ideas in Teigland et al. (2020).

The structure of the paper is as follows. Section 2 presents a brief background of underwater manimulators and control of ROVs. Section 3 describes the key idea behind the proposed single pilot methodology. It also provides a summary of inverse kinematics of manipulators and ROV motion compensation. In section 4, experimental results of testing the proposed controller on an industrial work class ROV are presented. Conclusions and suggestions for future research are summarized in Section 5.

In this paper we propose a new controller to enable one ROV operator to control the ROV and its tools. The controller is tested on a work class ROV.

2. BACKGROUND

Much of the work performed with ROVs involve using hydraulic manipulator arms. In general, control of these manipulators has been isolated from the ROV control and performed using a master controller that physically resembles the manipulator (Fig. 1). Via the controller, the operator controls each joint individually. Consequently, one pilot is required for operating the manipulator and this operator cannot perform other tasks since both hands are used on the controller.

Although various alternative control methods have been proposed in academia with some being tested on experimental ROVs, the use of more advanced controllers are very few in the industry.

2.1 Underwater manipulators

A work class ROV is usually fitted with two manipulators placed on each side at the front. Often, there is one five function manipulator (5FM) and one seven function manipulator (7FM); see Sivčev et al. (2018) for other type of underwater manipulators. The five and seven "functions" refers to the number of degrees of freedom (DOF) plus the gripper function. The 5FM is usually used for heavy duty tasks and is rate controlled without position feedback. The 7FM on the other hand is used for tasks where more dexterity is required and these are often fitted with position sensors, such as analog resolvers or digital encoders, in each joint to provide position feedback. In this paper, we mainly focus on the control of 7FMs with position sensor.

Fig. 1. Schilling T4 controller.

The 7FM manipulators in ROVs are usually anthropomorphic i.e., they resemble a human arm. They consist of 6 revolute joints plus a gripper (Fig. 2). The first two joints make up the shoulder joint, there is one joint for the elbow and the last three joints make up the wrist. From base to tip, these joints are commonly referred to as Azimuth, Shoulder, Elbow, Pitch, Yaw and Wrist.

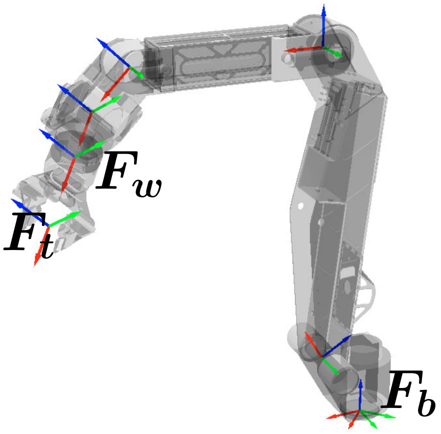

Fig. 2. The Schilling T4 manipulator with one frame at each joint. The frames referenced in this paper are labeled.

2.2 ROV and manipulator control

Although the ROV industry has witnessed many innovations over the last decades, there has been little changes in the way ROVs are controlled (Teigland et al. (2020)). A normal ROV operation involves three operators: One ROV supervisor responsible for overseeing the operation, reporting and communicating with the client and two ROV pilots. The pilots are responsible for the actual control of the ROV and divide the work into a pilot role and a co-pilot role. The pilot does most of the job which includes maneuvering the ROV, keeping control of the tether, controlling the five-function manipulator and other tasks. The main job of the co-pilot is to assist the pilot and to operate the seven-function manipulator.

Maneuvering the ROV is typically performed with a four axes joystick mapping the commands to thruster signals in surge, sway, heave and jaw, through a vectorization algorithm. Commercial manipulators are operated using joint rate or position control with an operator in the loop. The seven function manipulators are usually position operated through a pendant controller that mimics the arm.

Even though there has been little change in how ROVs are operated, there is a lot of research and innovation that has the potential to completely transform the way subsea operations are performed. Many of these are summarized by Teigland et al. (2020). In 2021 TechnipFMC launched their Gemini ROV SUT (2021), a state of the art ROV which feature a tool carousel and machine vision cameras. The cameras are used for automatic tool swap and as sensor input to the station keeping software through fiducial markers. The cameras can also be used to position the tip of the manipulator at the correct angle for performing work and the operator controls the ROV by a PlayStation controller. The approach that we have adopted in the current paper in essence is similar to the one by TechnipFMC. However, our approach can be used in existing ROV systems without much modification to the ROV itself.

2.3 Kinematics

We express the kinematics using screw notation as in e.g. Murray et al. (1994) and Lynch and Park (2017) with some notational differences.

For the purpose of this paper an abstract frame can be placed arbitrarily and can be defined to move with some joint. A frame at joint j is denoted F_j. The pose of a frame is expressed through transforms. For instance, the pose of F_j can be represented in some inertial frame F_i as T^i_j where T^i_j is in $SE(3)$.

Twist are spatial velocities and are always expressed in some frame. For instance, a twist expressed in frame F_j is expressed as

$$\mathcal{V}^j = \begin{pmatrix} \omega^j \\ v^j, \end{pmatrix} \tag{1}$$

where ω_j and v^j is the angular and linear velocity, respectively. The twist can be expressed in it's matrix form as

$$\hat{\mathcal{V}}^j = \begin{bmatrix} \hat{\omega}^j & v^j \\ 0 & 0 \end{bmatrix} \in se(3), \tag{2}$$

where $\hat{\omega}^j \in se(3)$ is the skew symmetric matrix form of ω^j. A twist defined in F_j can be expressed in F_i

$$\mathcal{V}^i = T^i_j \hat{\mathcal{V}}^j \left(T^i_j\right)^{-1}. \tag{3}$$

A twist can be "integrate" into a transform by interpreting the twist as a finite screw motion. Let the screw axis $\mathcal{S}^j$ be the normalized twist given as

$$\mathcal{S}^j = \mathcal{V}^j / \nu, \quad \nu = \begin{cases} \|\omega^j\|, & \text{if} \quad \omega^j \neq 0 \\ \|v^j\|, & \text{otherwise.} \end{cases} \tag{4}$$

Then, the screw axis $\mathcal{S}^j$ and a screw magnitude θ can be given as a transform from F_j to a new frame F_k through the exponential map

$$T^j_k = e^{\mathcal{S}^j \theta}. \tag{5}$$

If there is a rotational component to the screw axis i.e., $\omega \neq 0$ the exponential map is on the form

$$\begin{bmatrix} e^{\hat{\omega}^j \theta} & (I\theta + (1 - \cos\theta)\hat{\omega}^j + (\theta - \sin\theta)(\hat{\omega}^j)^2)v^j \\ 0 & 1 \end{bmatrix} \tag{6}$$

otherwise

$$e^{\hat{\xi}\theta} = \begin{bmatrix} I & v^j\theta \\ 0 & 1 \end{bmatrix}. \tag{7}$$

3. METHODOLOGY FOR SINGLE PILOT CONTROL

3.1 Single pilot control

In the following, we describe a proposed control method to enable single pilot control (SPC) where one ROV operator (or pilot) controls the ROV system. The main challenge in SPC lies in the way the manipulator is controlled since it makes it very difficult to perform joint ROV and manipulator control. It is important to note that the SPC must be possible even in the event of loss of e.g. station keeping capabilities which can happen quite often in practice.

The operator should not have to think about how the various controls are accessed. Rather, the controls should be readily available to the pilot (for example, when pilot uses the commends for the pan and tilt (PT) unit, he does not think about control surfaces but only specific functions). The PT unit has two motors that controls two axes, pan and tilt, and attached to the PT is one or more cameras. The pilots use this unit to point the cameras in various directions without having to move the ROV. Control of the PT is one example of controls that need to be readily available to the pilots.

3.2 Manipulator control

Our main goal in this section is to provide the operator with a controller that enables him/her to control the ROV manipulator with one hand. To this end, we will use a Cartesian control method instead of controlling each joint of the manipulator. In addition, we do not want to have a specialized controller to control the manipulator. Instead, we are interested in a controller that can be used for other purposes, like maneuvering the ROV. We propose to use a spherical 6-DOF controller which intuitively relates to controlling an ROV. Specifically, we propose to use a 3D mouse (3DM) or CAD mouse. The 3DM is developed to aid CAD engineers and is used to control the 3D object in the drawing. We want to do the same except that the object is a real object, namely the manipulator gripper. The output from the 3DM can be interpreted as ROV velocity or force output in the respective axis. In the following, we explain how the 3DM can be used to control the 7FM.

The output of the 3D mouse is interpreted as a twist $\mathcal{V}^a$ defined in some reference frame T^a. Picking this reference frame is not trivial and there are several possibilities, some more intuitive than others. The most naive way is probably by defining it from some inertial frame. However, considering that the manipulator moves with the ROV would mean that when the ROV is rotated 180° about the z-axis, pressing the controller forward would move the TCP towards the ROV, which is obviously not intuitive. Another approach is to define it from an ROV frame placed at the ROV center of gravity or from the base of the manipulator. The problem here lies in the use of the PT. If the PT is panned 90 degrees so that it is looking towards the starboard side of the ROV, pressing the controller forward would not move the TCP forward from the pilot's perspective. A third option then is to define the twist from the PT camera or some other camera so that the pilot controls the TCP from that camera. This is the method closest to the way 3DMs are used for CAD if the operator is looking at the camera from where the input is defined. However, there are multiple cameras on traditional ROVs to provide the operator with pictures from multiple views and to cover a wide area and the operator usually has views for multiple cameras on the screen at any time. This may become confusing for the operator. The cameras placed at the PT is usually the main camera in use but there are other cameras. In a future iteration one could imagine a system where the reference frame changes automatically based on which view the operator is looking at.

The discussion above refers to the reference frame for linear component of the twist. In a similar manner, the angular component may also be defined with respect to various reference frames, which may not be the same. Since we are only interested in changing the orientation of the twist, and not the magnitude, we only need the rotation component of the transform. Let ν^{rl} and ω^{ra} be the reference linear and angular components obtained from the 3DM input. These are then transformed to the target components ν^t and ω^t through

$$\nu^t = R^t_{rl}\nu^{rl}, \tag{8}$$

and

$$\omega^t = R^t_{ra}\omega^{ra}, \tag{9}$$

where $R^x_y \in SO(3)$ is the rotation of frame y, relative to frame x. The target in this case is the gripper or manipulator tip.

The resulting twist of the target $\mathcal{V}^t = \begin{pmatrix}\nu^t & \omega^t\end{pmatrix}^\top$ can be used directly in a velocity based inverse kinematics solver or it can be "integrated" over some time Δt to obtain a new transform for the tip. In the latter case, the transform between the base frame F_b and tip frame F_t is $T^b_t(t)$. The control system is updated with a frequency f. Assuming a constant twist during the time $\Delta t = 1/f$, we define the frame of the tip expressed in the base frame to be

$$T^b_t(t+\Delta t) = e^{\mathcal{S}^b \nu \Delta t}. \tag{10}$$

3.3 Inverse kinematics

We assume that the input to the manipulator is a joint position reference and that the manipulator is able to follow this as long as the joints are inside the joint limits. The reason for this assumption is that most manipulators are controlled by a pendant controller that sends joint position commands.

Let $q(t) \in \mathbb{R}^n$ be the joint reference positions and $x(t) \in \mathbb{R}^m$ be the pose corresponding to $q(t)$. These are related through the forward kinematics $f : \mathbb{R}^n \to \mathbb{R}^m$ which is a non-liner function that maps $q(t)$ to $x(t)$. Since we are working with a manipulator with six joints $n = m = 6$. The joint velocities are related to the twist through the geometric Jacobian $J(q) \in \mathbb{R}^{mxn}$

$$\mathcal{V}^t = J(q)\dot{q}. \tag{11}$$

In general, the pseudoinverse is used to solve for the joint velocities but since our $n = m$ we have

$$\dot{q} = J^{-1}(q)\mathcal{V}^t. \tag{12}$$

As noted, we require the joint positions, not the joint velocities. We perform a step-wise integration to compute the next position to be sent $q(t + \Delta t)$, where $q(t)$ is the last sent position reference and Δt is the time between each sent position. The integration is performed in k-steps, where k is a non-zero, positive integer depending on the time between each command and the time required to solve the inverse kinematics problem. Depending on Δt and the time required to solve the inverse kinematics. The integration is

$$q_0 = q(t) \tag{13}$$

$$q_i = J^{-1}(q_{i-1})\mathcal{V}^t \quad \forall \quad i \in [1..k]. \tag{14}$$

The implementation is based on the open source Kinematics and Dynamics Library (KDL) (see Smits et al. (2022) for details). Specifically, we use the inverse velocity solver which solves equation (12) while checking for singularities using singular value decomposition (SVD) based on Householder rotations. We use the inverse solver in each step of (14). If singularities are found then we set $q_i = q_{i-1}$.

To make the control more responsive, a feedforward term is added to the pitch and yaw joint such that

$$q_{k,F} = q_k + K_F\mathcal{V}^t\Delta t, \tag{15}$$

where

$$K_F = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & k_F \\ 0 & 0 & 0 & 0 & k_F & 0 \\ 0 & 0 & 0 & k_F & 0 & 0 \end{bmatrix}, \tag{16}$$

and k_F is determined experimentally based on operator feedback.

So far, joint limits have not been addressed or handled. Before outputting the new joint references, they are clamped between their upper and lower limits such that

$$q(t+\Delta t) = \begin{cases} q_{lb} & \text{if} \quad q_{k,F} < q_{lb} \\ q_{ub} & \text{if} \quad q_{k,F} > q_{ub} \\ q_{k,F} & \text{otherwise} \end{cases} \tag{17}$$

where q_{lb} and q_{ub} are the lower and upper bounds respectively.

3.4 ROV Motion Compensation

When the operator is working with the manipulator, the pilot will usually attempt to keep the ROV as stable as possible, relative to the object being worked on. This is because small motions of the ROV can lead to large motions at the manipulator tip. Because the ROV is fitted with sensors for attitude and depth measurements, these motions can be compensated for through transforms. The ROV compensation is started at time $t = t_0$. To this end, we need the following frames:

F_I , The inertial frame from which the measurements are taken from.
$F_b(t)$, Base frame associated with the actual manipulator position.
$F_b r = F_b(t_0)$, Base frame at start of ROV compensation.
F_g Frame associated with manipulator tip.

We solve the inverse kinematics problem in terms of the manipulator base i.e., we need to determine T_t^b. At each time-step, we receive a new input from the controller which is integrated to provide us with the transform T_g^{br}, which is the desired position of the gripper relative to where the base was at t_0. Thus,

$$T_g^b(t) = T_{br}^b T_g^{br}. \tag{18}$$

Since we gather measurements relative to the inertial frame, this can be rewritten as

$$T_g^b(t) = (T_b^I)^{-1} T_{br}^I T_g^{br}. \tag{19}$$

4. RESULTS

In an effort to verify the 3D mouse control, it has been tested on IKM Subsea's Residential ROV (RROV). The RROV is a work class ROV located at the Snorre B (SNB) oilfield. The 7-function manipulator used on the RROV is a Schilling Atlas manipulator.

The pilots were set to test the controller without any prior training with the controller in real life or in simulation. The test was completed over a couple of hours with two pilots trying out controller. In the beginning of the test, the pilots familiarized themselves with the controller by moving the arm around. Then they went on to more difficult tasks like grabbing objects and picking up tools from a skid on the ROV (Fig. 3). Finally, the pilots attempted to turn a bolt by using a subsea tool (Fig. 4). Both pilots were able to turn the bolt successfully although they used more time than they would have done using the pendant controller. This is not surprising considering that this way of controlling the manipulator demands another way of thinking. Also, both operators were senior operators with years of experience using the pendant controller. It may well be that this would come easier for inexperienced operators.

It should be noted that the ROV was grabbing a rail with the 5FM during the testing. This is a typical operation mode when working with the 7FM because it minimizes the motions of the ROV. The drawback is that it is not always possible to grab onto something. A benefit of this controller is that the operator can control the ROV with the hand that is not controlling the manipulator. Although this makes the operation more complex, it provides increased flexibility and potential for increased efficiency. Other solutions to this issue is discussed in later sections.

4.1 ROV Motion Compensation

The ROV motion compensation have been tested in simulation, using a kinematic model. The simulation is running in real time and the control system is updated at a rate of $100Hz$. The ROV heave, roll, pitch and heading have been simulated as sinusoidal motions according to Table 1. The pose of the tip has been recorded with and without motion compensation enabled. The pose shown in the results are measured relative to the initial pose since we want the tip to stay as close as possible to the initial pose. Fig. 5 shows the Euclidean distance from the tip to the origin and Fig. 6 shows the orientation of the tip relative to the initial orientation. The orientation difference is measured as the angle of the shortest arc between the quaternions. Both compensated and non-compensated motions are shown. The compensation scheme is able to remove almost all tip motion. There is some chatter in the pose of the tip under the compensation scheme which is why the blue lines appear thicker than the other ones. However, the chatter has very little effect in the joint angle commands which are shown in Fig. 7. One way of removing the chatter is by implementing a filter on the joint commands. The result of an exponential filter with time constant $0.5s$ are shown in the Figures 5 and 6. With the filter, the ROV compensation is significantly degraded. The filter also gives some hints as to how the compensation scheme would work in a real system, where dynamics and response delay come into effect.

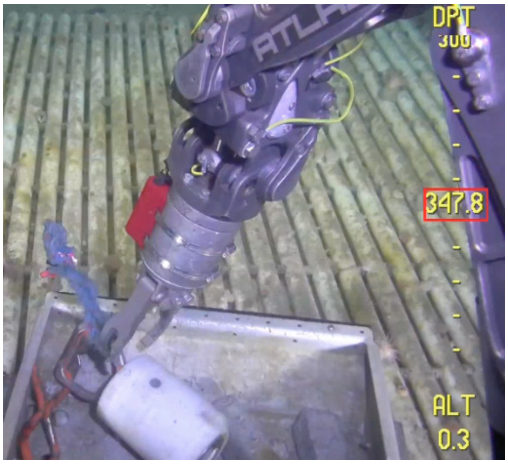

Fig. 3. Picking a tool from the skid.

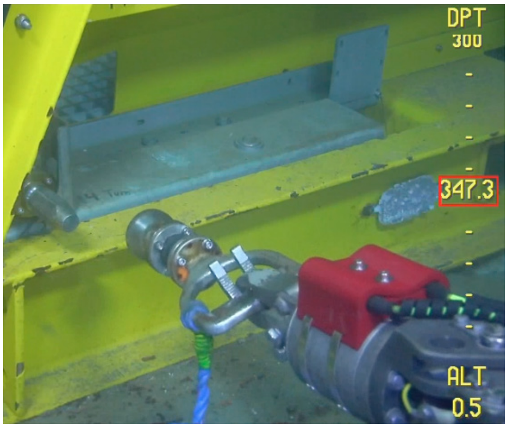

Fig. 4. Turning a bolt.

DOF	Amplitude	Period [s]	Phase [rad]
Heave	0.1 m	16	0
Roll	0.1 rad	8	0.1
Pitch	0.1 rad	12	0.2
Heading	0.1 rad	32	0.3

Table 1. Simulated ROV motions when testing ROV compensation.

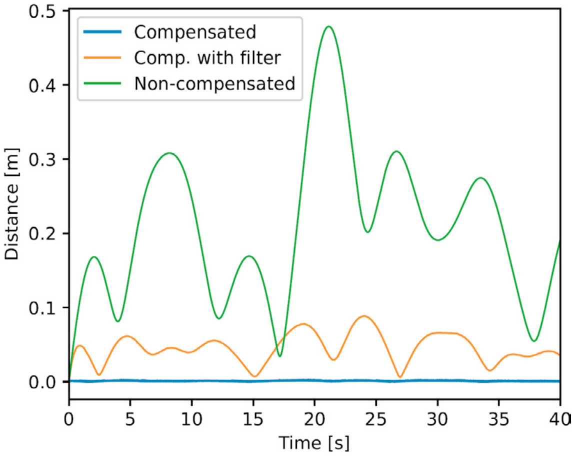

Fig. 5. Motion reduction of manipulator tip when ROV is moving with a heave, roll, pitch and yaw component.

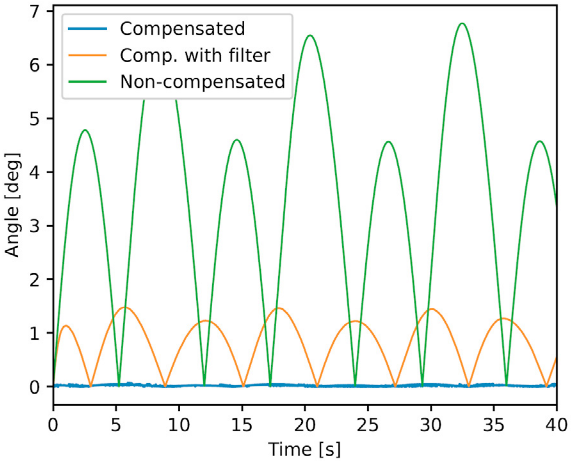

Fig. 6. Motion reduction of manipulator tip when ROV is moving with a heave, roll, pitch and yaw component.

5. CONCLUSION

This paper presented the results of developing a methodology that allows operation of industrial work class ROVs in smoother way using a single pilot. Pilot centric intuitive control of 7FM manipulator was presented. The developed framework was tested using IKM Subsea's Residential ROV (RROV), a work class ROV, located at the Snorre B (SNB) oilfield. The experiments showed effectiveness and simplicity of the developed framework. Industrial consequence of the developed methodology reflects in huge cost saving by reducing the number of required pilots for operation of ROV.

6. FUTURE WORK

The proposed controller can be extended by compensating for ROV motions and by extending the station keeping of the ROV so that it tries to keep the tip of the manipulator stable while moving the ROV so that the manipulator is in a favorable configuration.

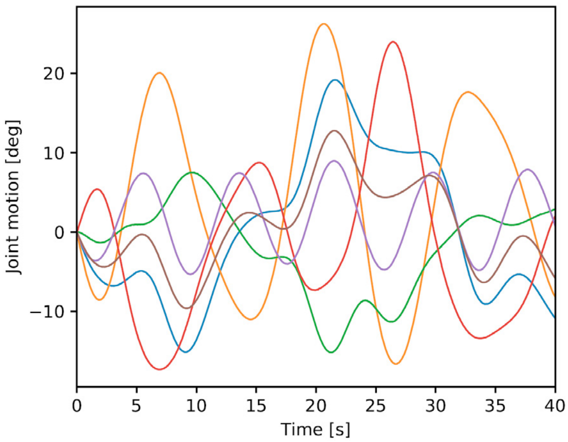

Fig. 7. Joint motions when ROV is moving with a heave, roll, pitch and yaw component.

Building on the previous argument we stress the importance of having a control method that is intuitive and simple to use. It is not uncommon to place a camera on the wrist of the 7FM. We propose to define the twist from the controller in this camera frame or in the wrist frame. This makes it possible to control the TCP by looking from this camera. The benefit of this method is that even though there is not camera there or the pilot is using another camera, this is still an intuitive control approach. The reason is that by placing the frame of reference at the wrist we are using the 3D mouse as it was design to be used. Namely to rotate 3D objects. The only difference is that the 3D object now is not a CAD model but a real-life object that happens to be placed at the end of a manipulator.

ACKNOWLEDGEMENTS

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