Abstract—This paper presents the development of underwater manipulator robot using commercial underwater servos. The proposed underwater manipulator system consists of Arduino MEGA microcontroller, position control joystick, 3 DOF underwater manipulator, and SimMechanics 3D Animation. The 3D Animation in the SimMechanics is utilized to visualize orientation of manipulator in the computer. Open loop control algorithm is embedded into Arduino MEGA using Simulink Support Package for Arduino Hardware. The kinematics of manipulator is studied using forward kinematics and inverse kinematics to investigate the motion of manipulator in the air. The forward kinematics is computed using mathematical approach based on D-H parameter, RoboAnalyzer, and SimMechanics. Mathematical approach using trigonometric method is employed to calculate the inverse kinematics. The motion study of the proposed underwater manipulator in the water is conducted by experimental work. Based on the experimental work, hydrodynamics effect gives steady state error and delay between command and response when underwater manipulator robot moves in the water. The proposed underwater manipulator robot integrated with SimMechanics 3D Animation has successful mission for underwater object grasping and manipulation both in the air and water.

Keywords—underwater manipulator; 3D Animation; SimMechanics; kinematics

I. INTRODUCTION

The utilization of manipulator robot is not only in industrial applications, but also in underwater exploration. The manipulator robots are widely used together with other underwater robots like remotely operated vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) in excavation and inspection operations, subsea installation support, searching for lost objects, sea-floor sampling, holding and tracking cables or wires and so forth [1]. The operator or user able to control manipulator robot using a small replica controller that integrated to the manipulator and 3D virtual reality as guided image. For position-controlled manipulator, the master controller directs the manipulator’s joints to move in response to movement of replica controller, which is known as unilateral control [2]. The controller and manipulator are integrated with 3D Animation. When the controller is operated, the manipulator and 3D Animation will follow the movement of the controller from user/operator.

The design of underwater manipulator is very challenging like choosing the actuator type, sensing, and control system. For the deep sea water the underwater manipulator robot usually use hydraulic actuator as has been developed by Wang [3] and Zhang [4]. The hydraulic actuator is utilized to overcome the high static pressure from hydrostatic in the water. The other actuators for underwater manipulator are DC motors. DC motor actuator has simpler and cleaner than hydraulic actuator. The modeling of underwater manipulator robot including the hydrodynamics acting as drag force has been developed by Li [5], Santhakumar [6], and Suboh [7]. The drag force resists the motion of underwater manipulator robot. The challenge for controlling underwater manipulator including the drag force is to compensate the drag force resulted from hydrodynamics effect. Many control schemes have been developed by researchers. Most of them have proposed the nonlinear control such as observer-based back stepping control [6], adjoin variable method [8], and neuro-fuzzy control [9]. Based on simulation results, the proposed nonlinear control is able to minimize the effect of hydrodynamics in the water.

The objective of this paper is to develop the constructing of low cost underwater manipulator integrated with position control joystick and 3D Animation. The study of forward kinematics and inverse kinematics is presented in section 3. The proposed of underwater manipulator will be studied experimentally and discussed in section 4. The conclusion will be drawn based on the comparison between the underwater manipulator commanded angle and it response.

II. SYSTEM HARDWARE AND SOFTWARE SETUP

In this study, a low cost Arduino MEGA microcontroller was used as the main controller of underwater manipulator robot. The Arduino MEGA is selected because it can be programmed using MATLAB/Simulink and has 16 analog to digital converter (ADC) pins, 54 digital input output (DIO) pins, 256 kB flash memory[10]. In the Simulink environment, it has Simulink Support Package for Arduino Hardware. This support package is compatible with many types of Arduino microcontroller [11]. The programming of Arduino microcontroller using Simulink Support Package for Arduino
Hardware is more effective and fast by using Simulink block diagram.

The underwater manipulator is designed to be commanded by user/person using position control joystick. It has three degree of freedom (DOF). Each joint angle is measured with angular potentiometer. Its joint angle of position control joystick corresponds with the joint angle of underwater manipulator. The design of position control joystick in SolidWorks and the final prototype can be seen in Fig. 1. The proposed of underwater manipulator has four waterproof servo motor. The waterproof servo motor is commercially available on the market. The underwater manipulator robot is tested in the shallow water approximately about one meter. Waterproof servo motor which has 10 kg.cm torques is used for joint one, two and three, while 4 kg.cm is utilized for gripper. Both of position control joystick and underwater manipulator are made of acrylic. Fig. 2 shows the underwater manipulator which is mounted on the ground. For the future implementation, the underwater manipulator can be mounted on underwater vehicle for underwater exploration in the shallow water.

![Fig. 1. (a) CAD design of position control joystick CAD design (b) Prototype.](image1)

![Fig. 2. (a) CAD design of position control joystick CAD design (b) Prototype.](image2)

After developing position control joystick and underwater manipulator, the next step is develop the block diagram in Simulink. It requires blocks form Simulink Support Package for Arduino, the blocks can access sensor and actuator via Arduino MEGA. Analog input block is used to measure the potentiometer on each joint of position control joystick and standard servo write is employed to drive servo motor on each joint of underwater manipulator. The reading from analog input is noisy. To overcome this noisy measurement, 2nd order low pass is implemented which cut of frequency of 50 rad/s. The angle command from position control joystick is transmitted using Serial Transmit block for 3D visualization in SimMechanics. The block diagram as shown in Fig. 3 is embedded in Arduino MEGA microcontroller using serial communication.

![Fig. 3. Embedded block diagram using Support Package for Arduino Hardware.](image3)

For visualization the orientation of manipulator, the manipulator in SolidWorks model, as shown in Fig. 2 is imported in SimMechanics using SimMechanics Link. SimMechanics Link is a CAD plug-in for exporting CAD assemblies from CAD software. The SimMechanics Link generates an XML file detailing the structure and properties of CAD assembly and 3-D geometry files for visualizing the various CAD parts [12]. The result of imported underwater manipulator model from SolidWorks to SimMechanics model can be seen in Fig. 4. In the figure, the block diagram is modified by adding Serial Configuration and Serial Receive block. The block is applied for receiving each joint angle of manipulator.

![Fig. 4. Block diagram 3D Animation SimMechanics.](image4)

The whole schematic of diagram hardware set up is shown in Fig. 5. Underwater manipulator system is supplied with 60 W DC power supply. User operates the underwater manipulator by moving position control joystick. The measured joystick motion of each joint is read by Arduino MEGA microcontroller. The measured signal is processed by 2nd order low pass filter and then drives servo motor on each joint of manipulator. The sample rate of subsystem in underwater manipulator system is summarized in Table I.
TABLE I. SAMPLING RATE OF UNDERWATER MANIPULATOR SYSTEM

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Sampling rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition of measured angle</td>
<td>100</td>
</tr>
<tr>
<td>Sending commanded joint angle to servo motor</td>
<td>100</td>
</tr>
<tr>
<td>Read sensor from position control joystick</td>
<td>100</td>
</tr>
<tr>
<td>Sending joint angle to SimMechanics 3D Animation</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Fig. 5. Schematic diagram of hardware setup.

III. KINEMATICS ANALYSIS

Kinematics analysis such as forward kinematics and inverse kinematics is one of the most important to study the behavior of manipulator robot. The computation of inverse kinematics is more complex than forward kinematics. Many computational software and tools have been used to solve the inverse kinematics such as MATLAB, SimMechanics, MAPLE, Adaptive Neuro-Fuzzy Inference System (ANFIS), RoboAnalyzer and so on. The literature that investigates a method for finding a neuro-fuzzy based solution to the inverse kinematics problem of robotic manipulators can be found in [13, 14, 15]. Adaptive Neuro-Fuzzy Inference System is utilized to solve inverse kinematics of 3 DOF and four DOF manipulator robot. Numerical algorithm based on fuzzy logic has been developed to solve the inverse kinematics of manipulator robot. Fuzzy logic is simple and fast for inverse kinematics solution [16,17]. A neural network-based inverse kinematics problem solution in manipulator robot has been developed in [18,19]. Based on the result study, neural-network-based inverse kinematics is able to minimize the error at the end effectors. Inverse kinematics solution using SimMechanics software under MATLAB/Simulink have been studied by ref. [20,21]. The simulation results show that SimMechanics method is much more effective and convenient. One of drawback using the SimMechanics program for simulation consists in solution of collision of bodies and in limitation of angles of joints.

In this paper, the study of the manipulator kinematics is divided into two sections. The first is about forward kinematics that is analyzed using mathematical approach based on D-H parameter, RoboAnalyzer, and SimMechanics. The second one presents inverse kinematics that will be developed using trigonometric method. The results of inverse kinematics will be given by predefined trajectory that must be followed by end-effector of the manipulator to calculate each joint angle.

A. Forward Kinematics

The purpose of manipulator robot kinematics analysis is to obtain the orientation and position of the end-effector from the base of manipulator. To describe the orientation and configuration parameters, Denavit-Hartenberg (D-H) method is used to provide forward kinematics modeling approach by default. To determine the D-H parameters, the initial position of proposed 3 DOF underwater manipulator is illustrated in Fig. 6 and the parameters for each link length is shown in Table II. The initial position of 3 DOF manipulator using D-H parameters can be summarized in Table III. The computation of forward kinematics in this study is developed in three different ways i.e, mathematically, SimMechanics, and Robo Analyzer.

TABLE II. PARAMETERS AND VALUES OF 3 DOF MANIPULATOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link length</td>
<td>$l_1$</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>$l_2$</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>$l_3$</td>
<td>23</td>
</tr>
</tbody>
</table>

Fig. 6. Initial position of manipulator robot.

TABLE III. PARAMETERS AND VALUES OF 3 DOF MANIPULATOR

<table>
<thead>
<tr>
<th>Link $i$</th>
<th>$a_i$ (cm)</th>
<th>$d_i$ (cm)</th>
<th>$\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>90°</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>0°</td>
<td>$\theta_2 + 90°$</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>0°</td>
<td>$\theta_3$</td>
</tr>
</tbody>
</table>

From the calculation results, the obtained equation to calculate the coordinates of the end-effector of manipulator is written as follows

$$
X = \cos \theta_1 (l_2 \cos \theta_2 + l_3 \cos (\theta_2 + \theta_3))
$$

$$
Y = \sin \theta_1 (l_2 \cos \theta_2 + l_3 \cos (\theta_2 + \theta_3))
$$

$$
Z = l_1 + l_2 \sin \theta_2 + l_3 \sin(\theta_2 + \theta_3)
$$

(1)
SimMechanics is utilized for computing the forward kinematics of manipulator. The input of each joint of manipulator is employed using joint actuator. The input is each joint angle on manipulator and the output is the position of end effector. The block diagram in SimMechanics model for computing the forward kinematics of manipulator is shown in Fig. 7. SimMechanics also has been successfully developed for 3D virtual hand in the previous research [22,23].

![SimMechanics model for calculating forward kinematics.](image)

**Fig. 7.** SimMechanics model for calculating forward kinematics.

RoboAnalyzer is 3D model based robotics software. It is utilized to assist in teaching and learning of robotics concept. This software will be used in research as a source of comparative analysis in forward kinematics. The given joint angle as follows \( \theta_1 = 60^\circ; \theta_2 = 120^\circ; \theta_3 = 30^\circ \), and the simulation results can be summarized in Table IV. The Table IV shows that there are no difference results among three methods.

**TABLE IV. PARAMETERS AND VALUES OF 3 DOF MANIPULATOR**

<table>
<thead>
<tr>
<th>Axis</th>
<th>Mathematics</th>
<th>SimMechanics</th>
<th>RoboAnalyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-26.34</td>
<td>-26.34</td>
<td>-26.34</td>
</tr>
<tr>
<td>Y</td>
<td>-15.20</td>
<td>-15.21</td>
<td>-15.21</td>
</tr>
<tr>
<td>Z</td>
<td>18.59</td>
<td>18.59</td>
<td>18.59</td>
</tr>
</tbody>
</table>

B. Inverse Kinematics Using Trigonometric Method

In this section, mathematical model approach will developed to solve the inverse kinematics of three DOF manipulator robot using trigonometric method. The resulted joint angles \( \theta_1, \theta_2, \) and \( \theta_3 \) from trigonometric method can be expressed as in equation from (2) to (6) as follows

\[
\theta_1 = \arctan \left( \frac{X}{Y} \right)
\]

\[
\theta_2 = \arctan \left( \frac{\sqrt{a^2 + b^2}}{c} \right) + \arctan \left( \frac{b}{a} \right)
\]

\[
\theta_3 = \theta_{23} - \theta_2
\]

Where \( a, b, c, \) and \( r \) are

\[
a = 2l_1 r
\]

\[
b = 2l_3 (z - l_1)
\]

\[
c = l_2^2 - l_3^2 - r^2 - (z - l_1)^2
\]

\[
r = \sqrt{X^2 + Y^2}
\]

The position of end effector will be given a trajectory with function of time as written in (7). The equations (2), (3), (4), and (5) are used to compute the inverse kinematics. The result of invers kinematics using trigonometric approach is described in Fig. 8. From the simulation, it can be seen that the solution of three DOFs inverse kinematics is successful, and efficient enough.

\[
x = 4t \sin(\pi t) + 15
\]

\[
y = -4t \cos(\pi t) + 15
\]

\[
z = 10
\]

**Fig. 8.** Inverse kinematics results of End-Effector for each joint.

IV. EXPERIMENTAL RESULTS

In this section, the motion study of underwater manipulator is conducted by experimental work in the water. To measure the joint angle on servo motor, the analog output voltage from potentiometer servo is fed into the analog input pin of Arduino MEGA. Then the measured voltage is converted into the corresponding unit angle in degree. The measuring of joint angle from potentiometer in servo motor can be seen in Fig 9.

![Analog output from servo motor potentiometer to measure the joint angle.](image)

**Fig. 9.** Analog output from servo motor potentiometer to measure the joint angle.

On the experimental set up, the underwater manipulator is driven by user using position control joystick. The angle change in each joint angle of position control joystick is measured using potentiometer installed on this stick. The
measured voltage from potentiometer in the position control joystick is processed using analog input pin of Arduino MEGA. The signal input from analog pin is filtered using second order low pass filter. The filtered angle of each joint on position control joystick is utilized to drive the servo motor actuator on each joint of underwater manipulator. Measured angle input from position control joystick is sent to computer using serial communication via USB. The data is utilized to visualize the orientation of underwater manipulator in SimMechanics 3D Animation. The experimental set up in the air and in the water can be seen clearly in the Fig. 10 and 11 respectively.

After the set up for hardware and software is completed, the command and response of underwater manipulator commanded using position control joystick will be compared both in the air and in the water. The measured joint angle is joint 2 and joint 3 which are driven by higher torque motors. The experimental results for joint 2 and joint 3 are shown in Fig. 12 and 13 respectively. Fig. 12 reveals that in the air the response of joint 2 occurs oscillation and delay. Oscillation on joint 2 is caused by vibration on the joint 2 and the joint need more torque than other joint. The delay on joint 2 is caused by second order low pass filter and the dynamics of manipulator in the air. When in the water the delay and steady state error become large. This is clearly caused by hydrodynamics effect of water. Fig. 13 shows the joint angle 3 when commanded by user using position control joystick. In the air, the link 2 of underwater manipulator has less steady state error and delay compared to link 2 of underwater manipulator when it moves in the water. Based on the experimental results, the hydrodynamics effect gives large steady state error and delay between input command and response.
V. CONCLUSION

This paper proposes the development of low cost underwater manipulator robot which aims to grasp and manipulate an object in the shallow water. The block diagram of underwater manipulator is embedded into Arduino MEGA microcontroller using Simulink Support Package for Arduino Hardware. Three DOF position control joystick is utilized to give commanded joint angle to underwater manipulator from user. 3D Animation in SimMechanics is applied to visualize position and orientation of underwater manipulator on the computer sent by Arduino microcontroller via serial USB. The proposed system has sampling rate of 100 Hz for data acquisition of measured angle, sending commanded joint angle to servo motor, read sensor from position control joystick and sampling rate of 0.25 Hz for sending the measured joint angle to visualize the orientation of underwater manipulator in SimMechanics3D Animation. The study of forward kinematics of manipulator in the air is employed using mathematical approach based on D-H parameter, RoboAnalyzer, and SimMechanics. Based on the simulation, the three methods have the same results. The developed mathematical approach using trigonometric method is able to calculate inverse kinematics of 3 DOF manipulator. As can be seen on the experimental results, hydrodynamics effect gives large steady state error and delay between command and response when underwater manipulator moves in the water. Although the manipulator has steady state error and delay, the proposed underwater manipulator robot integrated with SimMechanics 3D Animation has successful mission for underwater object grasping and manipulation both in the air and in the water. In the future study, nonlinear control of underwater manipulator robot is needed to reduce the steady state error and delay.

REFERENCES