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# Theory and Design Issues of Underwater Manipulator

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## Abstract

In this paper we discuss the theory and implementation issue that is faced by underwater manipulators designers. It is collective information and method that was extracted from work by previous researchers. The paper presented some of the modeling parameters which is normally included in the underwater robotic designs which are add mass, added corriolis, drag force and buoyancy. Simulations of all these parameters were run using the MATLAB by modifying some of the code which was created by Peter Corke through his robotic toolbox. A comparison between land based design and underwater manipulator design were done which indicates an increase in the torque required to make similar movement in the link joints due to the added parameters as the manipulator perform its work underwater. In this paper we have used the PUMA 560 configuration which is generated inside the robotic toolbox as our manipulator tool. The paper then concludes with next direction of the project and improvement.

## 1. Introduction

Oceanic exploration has become an emerging field of research due to many human resources which is located beneath the deep sea. Deep sea exploration poses a different challenge to human being since we are not able to withstand the harsh condition that it poses. Therefore robotic research has come into place in order to prevent human intervention in the deep sea. Current field of intense research focuses on the development and deployment of AUV (Autonomous Underwater Vehicle) which is able to maneuver itself into the deep ocean. This will remove human from being exposed to the hazardous environment during underwater exploration. Some of the application of the AUV includes inspection whereby the AUV is equipped with camera to perform its duty to inspect the surrounding of the required area. Underwater AUV are expected to play a vital role in the future in replacing humans from the danger of ocean exploration.

Manipulator design and application is another area of intense research which will enable robot to replicate the function of the human arms and hands. Various applications have been researched such as the use for placing and screwing assembly parts. Manipulator design are normally governs by the number of degrees that it is able to perform or 'manipulate' itself or in other words DOF (degrees of freedom). Degree of freedom refers basically to the number of joints that the manipulator possesses. The higher the number of DOF means that the manipulator is more flexible to move around. Joints can be classified into two different types which are the prismatic and revolute. Prismatic joints are joints that are making translational motion while revolute joints are joints which are able to make rotational motion.

Underwater Vehicle Manipulator System (UVMS) has gain popularity in the robotic research community as it offers underwater robots more flexibility and wider range of application. More application which previously requires the guided arms of human is being replaced by the more dexterous robotic manipulator. Underwater vehicle which are equipped with manipulator are able to perform various task such as picking up object from the ocean bed, drilling, joining parts and even part assembly. This is only possible with the use of better design existed in the manipulator.

Underwater Vehicle Manipulator System poses a different challenge upon interested researcher due to the fact that it has to take the consideration of the hydrodynamics that existed underwater. This includes the added mass, buoyancy, drag and friction. This will change the dynamics of the manipulator due to the added effect from the hydrodynamics.

The objective of this paper is to discuss some of the design consideration that has to be included when equipping underwater vehicle with manipulator. In this paper attention are given towards five aspects of the design criteria which are the DOF, workspace extent, end effector maximum speed and repeatability and accuracy of the manipulator. In this paper we have conducted simulation to show the difference between the underwater manipulator and surface manipulator by including the hydrodynamic effect in the dynamic function of the manipulator. For this test we have use 6 DOF of PUMA configuration with all revolute joints to replicate the end effector positioning. All the links parameters are properly specified such as the moment of inertia tensor, gravity the gear ratio and friction.

Among parameters that were simulated are the change mass change in the link parameters and also the buoyancy change. All the simulation was conducted in the MATLAB workspace by utilizing the robotic toolbox function. The comparison focuses on the torque requirement in order to achieve the assigned position between manipulator which operates underwater and also the surface. The torque is obtained by using the inverse dynamic algorithm of recursive newton euler method, which calculates the torque based on the position, velocity and acceleration of the joints. From the analysis and simulation a fair conclusion was made indicating how much the change of the hydrodynamic will impact the movement of the underwater manipulator and thus will ensure enough consideration given towards this factor in the underwater manipulator design. By utilizing the power of simulation we are able to observe the effect on our torque value as we vary certain parameters in the hydrodynamics. This will ensure a better design of the manipulator.

## 2. Design Consideration

Underwater Vehicle Manipulator System poses a different challenge upon interested researcher due to the fact that it has to take the consideration of the hydrodynamics that existed underwater. In this paper attention are given towards five aspects of the design criteria which are degree of freedom (DOF), workspace extent, load carrying capacity, end-effector maximum speed and the repeatability and accuracy of the manipulator are needed to be considered. Besides that, it is very important to know about the kinematics and dynamic motion of manipulator. Kinematics is a study of motion without regard to the forces which cause it. The kinematics of manipulators involves the study of the geometric and time based properties of the motion, and in particular how the various links move with respect to one another and with time. Of more use in manipulator path planning is the *inverse kinematic solution* which gives the joint angles required to reach the specified end-effector position. The solution is regarding to the Denavit-Hartenberg notation to identifying joint-link parameters. Manipulator dynamics is concerned with the equations of motion, the way in which the manipulator moves in response to torques applied by the actuators, or external forces. The general equation of motion for an *n*-axis manipulator are given by

$$\boldsymbol{\tau} = \mathbf{M}\,(q,q'') + \mathbf{C}\,(q,q\,')q' + \mathbf{F}(q') + \mathbf{G}(q)$$

If *added mass*, buoyancy, hydraulic drag and friction are added on the underwater manipulator dynamics. As the robot moves underwater, additional force and moment coefficients are added to account for the effective mass of the fluid that surrounds the robot and must be accelerated with the robot. These coefficients are meant by *added (virtual) mass* and include added moments of inertia and cross coupling terms such as force coefficients due to linear and angular accelerations. Dynamic equation of an underwater manipulator which has *n*-joints is as follows:

$$\boldsymbol{\tau} = \mathbf{M}\,(q,q'') + \mathbf{C}\,(q,q')q' + \mathbf{F}(q') + \mathbf{G}(q) + \mathbf{D}(q,q')$$

where $q$ is the joint angular position, $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{C}$ denotes the Coriolis, centrifugal forces, $\boldsymbol{G}$ represents the gravity forces which include buoyancy effects, $\boldsymbol{F}$ is the friction terms, $\boldsymbol{D}$ is the hydraulic drag forces which caused by the relative velocity of manipulator to ocean current and waves, $\boldsymbol{\tau}$ is the vector of applied joint torques which are actually control inputs,

### 2.1 Dof (Degrees of Freedom)

The number of independent movements that the manipulators can perform in a 3-D space is called the number of degrees of freedom. Manipulator arms can provide multiple degrees of freedom, as shown on the following figure1 of the advanced Kraft TeleRobotics Predator-7. Basically, there are two types of movement for manipulator which is translation and rotation. Translation represents linear motions along three perpendicular axes, specify the position of the body and rotation represents angular motions about the three axes, specify the orientation of the body. The determination of dof depends on the task of that manipulator. A common strategy in design is to put a 3-dof base to achieve arbitrary position, and add a 3-dof spherical wrist to achieve arbitrary orientation. Often the task at hand does not require a full 6-dof, e.g. when task objects exhibit symmetry, or when no obstacle in workspace, or simply when the task involves limited directions of movement. Obviously, it is optimum to design the manipulator with the minimum dof that will achieve the task. This reduces cost and simplifies the analysis. Most of the commercial underwater manipulators operate by mounting on the underwater vehicles. Some of them are just designed with a small number of dof because the vehicle itself has its own dof. However, JASON has a general purpose manipulator with six dof. Figure2 shows the manipulator arm of JASON.

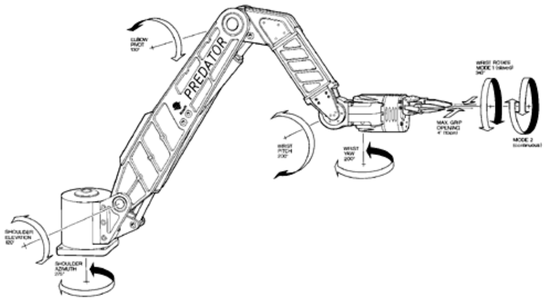

Figure 1 : Kraft TeleRobotics Predator-7

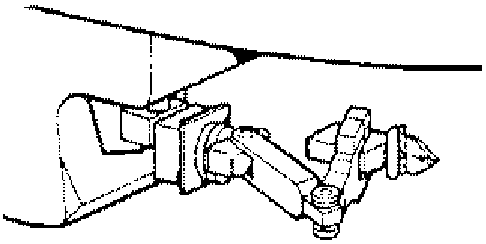

Figure 2 : Manipulator arm of JASON

## 2.2 Workspace extent

The workspace of a manipulator is defined as the volume of space in which the manipulator is able to locate its end-effector. Thus, in this analysis the workspace is referring to the underwater surrounding. Sometimes the shape of the workspace needs to be considered. The manipulator workspace is characterized by the mechanical joint limits in addition to the configuration, link length and the number of degrees of freedom of the manipulator. The workspace gets specified by the existence or nonexistence of solutions to the inverse kinematics problem. The region that can be reached by the origin of the end-effector frame with at least one orientation is called the *reachable workspace* (RWS). If a point in workspace can be reached only in one orientation, the manipulatability of the end-effector is very poor and it is not possible to do any practical work satisfactory with just one fixed orientation. It is, therefore, necessary to look for the points in workspace, which can be reached in more than one orientation. The space where the end-effector can reach every point from all orientations is called *dexterous workspace* (DWS). If no solution can be determined for a particular manipulator pose that configuration is said to be *singular*. These singularities represent the boundary and/or the internal singularities. Surface patches corresponding to these singularities represent the singular surfaces within the workspace. As it is impossible to move the tip of the manipulator along the singular surfaces, no matter which joint rates are selected, they are to be avoided during manipulation. Any point lying on a singular surface will have zero manipulability.

## 2.3 Load carrying capacity

The load required to be carried by the robot will govern the size of its motors, and the structural integrity of its joints and links. For the same level of structural integrity, the payload capacity will decrease as the workspace volume increases.

## 2.4 End effector maximum speed

The faster a task can be achieved, the more viable is the robot compared to hard automation or human workers. Cycle time, the time taken to achieve a complete move, is a function end-effector speed, but also on the accelerations possible during the acceleration and deceleration phases. So acceleration capability is also of importance.

## 2.5 Repeatability and accuracy

This is one of the critical properties of any robot. Constructing a robot with high accuracy and repeatability is expensive: stiffer links, tighter tolerance joints, position sensing, and modeling and etc. The aim should be for the minimum accuracy and repeatability required by the task. External sensing, particularly force sensing, is a means in many tasks to reduce the required level or accuracy. This has been and still is a current active research area.

## 3. Manipulator Kinematics and Dyanmics

In this section we will reviewed the 2 important aspect of designing of robotic manipulator. Robotic manipulator is required to follow a trajectory to manipulate a certain object and to perform the task required in its given workspace. The first aspect is the kinematic analysis of the manipulator and the second parameter is the dynamics.

### 3.1 Kinematic

Kinematic model describes the spatial position of the joints and links and position and orientation of the end-effector [1]. It is basically a way to establish a relationship between the joints variables and the link position and orientation. The forward kinematics involves the process of establishing the position and orientation of the end effector with based on the joint variables. Inverse kinematic on the other hands involves relates the joint variables when the end effector position and orientation has been ascertain. In this work we have used the Denavit-Hartenberg convention in naming the link and frame. This corresponds with the method which is also been applied to the torque computation which is been used by Peter Corke [2].

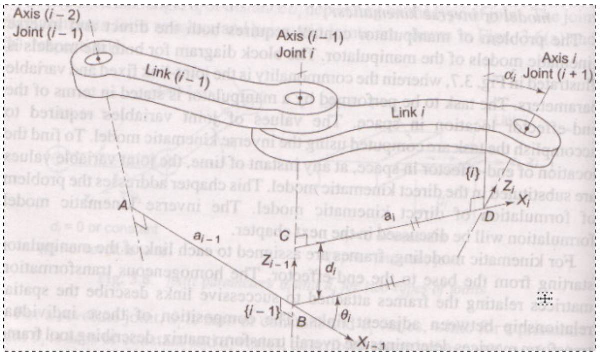

Figure 3 : Denavit-Hartenberg Convention [1]

As we can see in this frame naming convention the frame *i*, for link *i* is located at the distal end of the link. The following are the definition for the link parameters.

i) Link length, $a_i$
ii) Link twist, α is the angle of between $z_i$ and $z_{i-1}$ which is read from $x_i$.
iii) Link offset, $d_i$, is the distance from origin of frame {i-1} to frame {i}.
iv) Joint angle, Θ, is the angle between the $x_{i-1}$ to $x_i$ from $z_i$

Another convention that is being used is the modified denavit-hartenberg convention which utilizes the frame{i} to be the same as joint{i}[3]. The linear velocity of frame *i,* will be determine by the following equation

$$v_i = v_{i-1} + {}^{i-1}\dot{D}_i + w_{i-1} \times {}^{i-1}D_i$$

i, is the frame
D, is the position matrix with respect to frame i

The angular velocity of the link with respect to the base frame is described as follows

$$w_i = w_{i-1} + {}^{i-1}w_i$$

w, is the angular velocity

### 3.2 Dynamics

Dynamic behavior of a robotic manipulator is defined as a time-varying movement of the manipulator. This time varying movement is controlled by the torque which is applied through the link joints. The internal torque generated is caused by the motion of the links itself while the external force which acts upon the links includes load and the gravitational forces. There are a number of dynamic modeling method which is applicable. The most common are the Langrange-Euler (LE) and Newton-Euler (NE). Tarn, Yang, Shoults [4], has used kane's method instead for their dynamic modeling of underwater manipulator.Kane's method is a combination of both EL and LE. In this method it actually eliminates the non-working link interaction forces. In this paper we have simulated the dynamics using the NE. The newton euler methods relys on the fundamental principle of newtons motion law and the d'Alembert principle. The force that is action at the center of the mass of the link is given by

$$F_i = m_i \dot{\bar{v}}_i$$

*F, Force*
*m, mass,*
$\dot{\bar{v}}_i$ *linear acceleration of the link*

The euler equation for rotational movement is defined and characterize by the following equation. The angular velocity, $w_i$ and the moment of the inertia tensor $I_i$ relates to the total moment, $N_i$ as follows

$$N_i = I_i \dot{\omega}_i + \omega_i + (I_i \omega_i)$$

In the recursive newton euler method, involves two part of computation. The first part is the forward iteration which involves the calculation of the velocity and acceleration starting from the base and moving towards the end-effector. The second part is the backward iteration whereby we use the velocity and acceleration that was computed initially and starting from the end-effector to calculate the force and moment and moving backwards towards the base frame. The following equation summarizes the backward iteration calculation

$$ {}^{i}F_i = m_i \; {}^{i}\dot{\bar{v}}_i $$

$$ {}^{i}N_i = I_i\dot{\omega}_i + \omega_i + (I_i\omega_i) $$

$$ {}^{i}f_i = \; {}^{i}F_i + \; {}^{i}R_{i+1}{}^{i+1}f_{i+1} $$

$$ {}^{i}n_i = \; {}^{i}R_{i+1}{}^{i+1}n_{i+1} + (\; {}^{i}R_0{}^{i-1}D_i) \times \; {}^{i}R_{i+1}{}^{i+1}f_{i+1} + \\ (\; {}^{i}R_0{}^{i-1}D_i + \; {}^{i}R_0 \; {}^{i}\bar{r}_i \times \; {}^{i}F_i + \; {}^{i}N_i $$

$$ \tau_i = \begin{cases} {}^{i}f_i^T \; {}^{i}R_{i-1}\widehat{z_0} & \textit{prismatic joints} \\ {}^{i}n_i^T \; {}^{i}R_{i-1}\widehat{z_0} & \textit{revolute joints} \end{cases} $$

whereby ${}^{i}R_{i+1}$ is the rotational matrix of frame {i+1} with respect to frame {i}, D is the position matrix. f and n is the force that is acting at the joints itself. τ is the torque which is required for the joints which depends either the joints are prismatic or revolute.

## 4. Hydrodynamics

In order to accurately model underwater manipulator, we are required to take into account additional effect that is caused by the motion of the incompressible fluids itself. These forces are a result from incompressible fluids which is determined by the Navier-Stokes equation[5]. In this paper we would consider 4 major hydrodynamics effect which are the added mass, added coriolis and centripetal, drag force and buoyancy.

### 4.1 Added Mass

The added mass is generated when a rigid body moves in a fluid. The fluid will also be accelerated by the movement of the body which requires an additional force. This effect is neglected in typical industrial robotic due to the low density of the air compared to water which has almost similar density as the underwater vehicle[6]. The fluid will exert a reaction force from the movement of the fluid which contributes to the added mass. By approximating the manipulator as slow moving and which has 3 planes of symmetry as common for underwater vehicles the added mass will take a diagonal form of a 6 × 6 matrix. This will give the added mass the following form as per Fossen[7]

$M_A = M_A^T = -\mathrm{diag}\{X_u, Y_v, Z_w, K_p, M_q, N_r\}$

The added mass for the manipulator will be derived by approximating the links as cylinders. For a cylinder oriented such that the length of the cylinder is along the x-axis the added mass inertia matrix can be approximated as follows

$X_u = 0$
$Y_v = \rho\pi r^2 L/4$
$Z_w = \rho\pi r^2 L/4$
$K_p = 0$
$M_q = \rho\pi r^2 L^3/12$
$N_r = \rho\pi r^2 L^3/12$

### 4.2 Drag Force

The drag force exerted on the links of the manipulator will be modeled based on strip theory. Strip theory is used by replacing the surface integral with a line integral along the length of the links cylinder. The cylinder is broken into small segment and individual forces acting on the segment is calculated. The drag force is related to the drag coefficients which is a function of reynold numbers. Different drag coefficient was presented by Antonelli[6]. The drag coefficient can be modeled by using the following equation[8]

$$ \tau = - \sum_{i=1}^{n} C_d \left(\frac{l_i\theta}{D}\right) * 0.5\rho D l_i^3 \, dl_i \left|\dot{\theta}\right|\dot{\theta} $$

whereby $C_d$ is the drag coefficient, D is the diameter of the cylinder, θ is the joint displacement, l is the distance from the joints to the segmented length.

### 4.2 Buoyancy

Buoyancy is the force which is created due to the volume of the fluid displaced by the submerged body. It is exerted at the center of buoyancy of the body which is the center of the volume displaced by the body[5]. This buoyant force is acting in opposite direction of the gravity force. The gravity force of the submerged weight of the body is defined as

$W = mg$
whereby g is the vector of the gravity acceleration which is acting on the center of the mass. The buoyant force on the other hand is made of the following equation

$B = \rho V g$

where V is the volume being displaced by the body.

## 5. Simulation and Discussion

Simulation was done using the MATLAB platform whereby the by using the default parameters of the puma560 inside the robotic toolbox which was written by Corke. The built in recursive newton euler function was modified in order to include the hydrodynamics parameters. Comparison was done to see the impact of this parameters towards the total torque which is required to be supplied by the motor. The path trajectory of the manipulators was initialized using the *jtraj* function from the robotic toolbox. This function will generate the joint's position, velocity and acceleration within the specified interval time. It is based on a fifth order polynomial. The joint position, velocity and acceleration is shown in figure 4,5,6 respectively

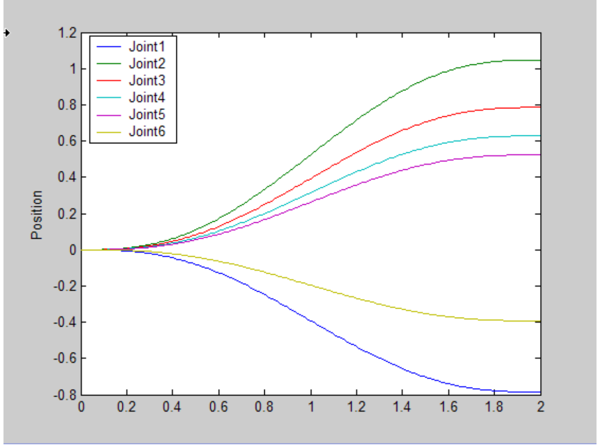

Figure 4 : Joint Position Plot

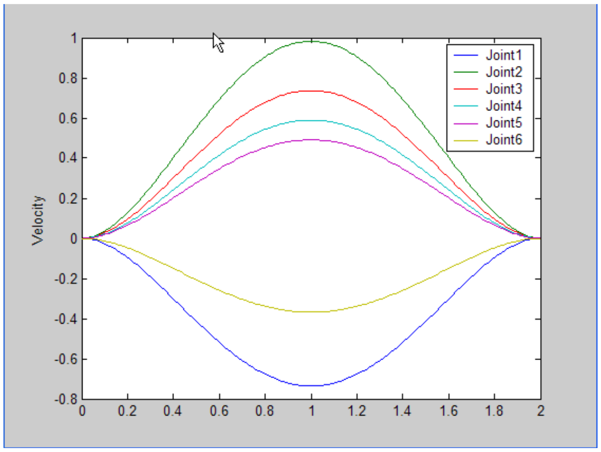

Figure 5 : Joint Velocity Plot

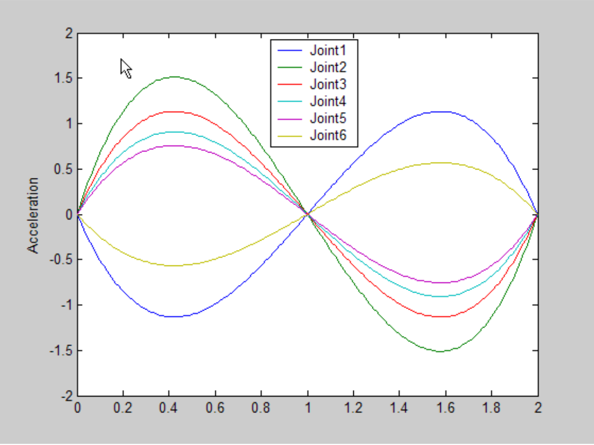

Figure 6 : Joint Acceleration Plot

The velocity and acceleration is basically obtained by taking the differentiation of the position values. The torque which is required if the manipulators were required to work on land is plotted in Figure 7 , The joint4,5 and 6 requires very low torque due to its low mass and moment of inertia as expected from a puma robot. Figure 8 shows the torque requirement when adding the hydrodynamics effect. It is observed that joint4,5,6 does not exhibit a significant increase in the torque requirement. This can be relate to the fact that the length of these joints are equal to zero which means that the drag force will be equal to zero so does the added mass. Overall there is no significant increase in the torque requirement due to the small dimension of the link manipulator. This is understandable since most of the hydrodynamic mostly relies on the dimension of the manipulator links itself.

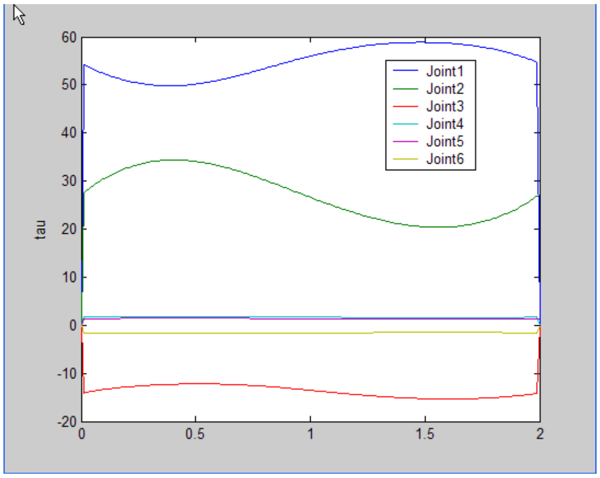

Figure 7 : Torque without Hydrodynamics

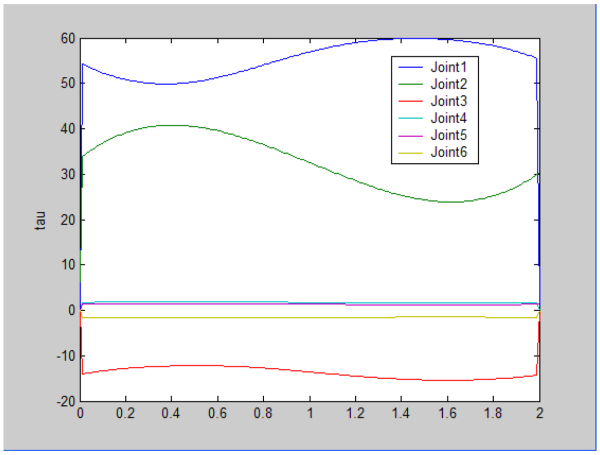

Figure 8 : Torque with Hydrodynamics

## 6. Summary and Future Work

The hydrodynamic equation has been successfully integrated with the normal manipulator dynamics. By including simulation in the development work of underwater manipulator this will prevent the need of simulating the problem using real manipulators which will be cost intensive. In this paper we have presented a method of simulating the torque requirement of a puma 560 configuration underwater using MATLAB as our simulation platform. Since we have created the model inside the MATLAB we are able to vary various parameters in order to see the effect of each of these parameters towards the torque requirement of the joints. This will help us in understanding what will be the torque requirement for each joint which will help to generate the design criteria of the actual manipulators. One thing to take note is that normally underwater manipulator will be attached to an AUV which means that the modeling has to take into account the fact that the manipulators are attached to mobile base. McMillan suggested that the mobile base can be modeled as another link (link 0).

This paper only discusses the requirement and challenges that will be faced by researchers in designing a working underwater manipulator. The work is still at an infant stage whereby real physical modeling has not been started. The simulation capability which is provided by the MATLAB program will assist researchers is understanding and developing an offline working model which can be tested before design the 'real' thing.

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