Development of a tentacle propulsion technique for underwater application

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Abstract. As robotic technology matures and more platforms are fielded in unstructured real-world situations, the more new areas of applications are being thought for robotic deployment. After successes in industrial robots, researchers are now trying to explore new robots with biological features of different biological creatures like, snake, bird, and spider for their stunning advantages. Underwater exploration using robots is a new avenue. Research on the tentacle robot for underwater application is a new field of research besides the other research in this arena. There are few researches on this topic are explored and mostly are on biological robot. Besides those researches this paper aims to propose and demonstrate another technique to build a tentacle for propulsion purposes. Therefore, in this paper will discuss more on mathematical development for the propulsion technique and its software verification technique in considering the environmental constrains.

1. INTRODUCTION
As robotic technology developed and more focusing area are explored in unstructured real-world situations, the more new areas of applications are being discover for robotic deployment. After successes in industrial robots, scientist are now trying to explore new robots with biological features of different biological creatures like, snake, bird, spider for their vivid advantages. The various contributions on bio-inspired or bio-mimetic have been increasing dramatically throughout the last decade [1]. Bio-inspired robotics reflects the features and capabilities of natural evolution of a system that could be efficiently replicated or mimicked in a human developed system to design the new technologies and improvement of conventional systems [2]. Underwater exploration using robots is a new avenue [3]. However, fish robot cannot be expected to manipulate objects or undertake maintenance operation underwater, it can only do surveillance activities [4]. But we need multitasking underwater robots, especially one that would be able to propel itself, as well as manipulate objects. A robot that would be able to mimic natural tentacle is a probable solution. In the design and development of tentacle robot, tentacle would play the vital role. Tentacles can be regarded as continuum robot (continuous backbone).Tentacle robot is one of the features in underwater robot created from a sequence of link and joint combinations. The links are rigid members connected by the joints or axes. Whereas the axes are movable component of the tentacle robot that causes relative motion between adjoining links. These joints can be classified in different categories. One of them is

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kinematic analysis which analysis the robot structure topologies such as serial robotic manipulator, parallel manipulator or hybrid robotic manipulator. For any model analysis the analysis can be done in four ways which are: a. Forward Dynamics analysis, b. Inverse dynamics analysis, c. Kinematic analysis and d. trimming analysis methods. For a close loop system the problem is solved mathematically by forward kinematics where individual body mass, acting force, torque and mass moment of inertia are known. The degree of freedom DOF are also predetermined once solving a mechanical problem in Forward dynamics method. For determining the forces/torques system has to be given a set of motions that required applying to the machine can be solved by reverse dynamics. This mode only works with open topology systems whereas the model diagrams is prepared in open loops [1]. The paper focuses on the modelling, Simulation and development studies of an underwater tentacle robot. The works in this paper more specifically identifies the prospects of the tentacle robot and identifies the individual joins position velocity and acceleration needed in the real environment in considering the environmental constrain to the model for simulation.

Since the proposed tentacle is usually an open ended tentacle therefore, an inverse kinematic mathematical and simulation model is designed to identify the required angular position, velocity and acceleration for each joint to acquire the defined location of each link in a particular time.

2. MODEL DESIGN

The kinematics control problem focused upon the computation if the joint positions required in locating the end-effectors’ at desired Cartesian position and orientation. The design of kinematics control algorithms involves formulation of kinematic model, inversion of kinematic model and the implementation of inverse kinematics algorithms. However, the most difficult task in the kinematics control algorithm is the formulation of the inverse kinematic model.

A. Inverse kinematics solution (IKS) by mathematical model:

IKS for Two Links Manipulator is simple and the closed from IKS is presented below:

\[ x = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) \]  \hspace{1cm} (1.1)
\[ y = l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) \]  \hspace{1cm} (1.2)

Solving (1.1) and (1.2) for \( \theta_1 \) and \( \theta_2 \), the inverse kinematics solution can be obtained, which is shown in the following steps:

![Mathematical model diagram of a two link manipulator.](image)
Here, "+" sign is used for CCW configuration and "−" sign for CW configuration. By expanding (1.1) and (1.2), the following are obtained,

\[ \text{Cos}\theta_2 = \frac{x^2+y^2-l_1^2-l_2^2}{2l_1l_2} \]  
\[ \text{Sin}\theta_2 = \pm \sqrt{1 - \text{Cos}^2\theta_2} \]  

(1.3) \hspace{1cm} (1.4)

Where, \( K_1 = (l_1 + l_2\cos\theta_2) \) and \( K_2 = l_2\sin\theta_2 \)

Simultaneous solution of Equations (1.5) and (1.6) gives,

\[ \text{Sin}\theta_1 = \frac{K_1y-K_2y}{k_1^2+k_2^2} \]  
\[ \text{Cos}\theta_2 = \frac{K_1y+K_2y}{k_1^2+k_2^2} \]  

(1.7) \hspace{1cm} (1.8)

Thus the joint variable \( \theta_1 \) and \( \theta_2 \) are obtained from the following two equations:

\[ \theta_1 = \text{atan}2(\text{sin}\theta_1, \text{cos}\theta_1) \]  
\[ \theta_2 = \text{atan}2(\text{sin}\theta_2, \text{cos}\theta_2) \]  

(1.9) \hspace{1cm} (1.10)

It is showed that the above IKS of the 2-link tentacle input link length, coordinates of base and desired points with sign configuration will provide a unique solution for any IKS problems. However, once the number of links is increased than it raises new complexity in solving that problem. Any Hyper Redundant Robot (HRR) can be considered as a robot consisting of 2-links robot and provided IKS of 2-links can be used repeatedly for the IKS of the HRR. Therefore, this method can be extended to in considering one joint at a time to solve the multilink tentacle desired location and angle. This complexity can be solved more efficiently in making a software simulation and mimic the same sort of response curve for different link of a tentacle.

**B. Solidworks model design for the proposed tentacle:**

Solidworks, as the mainstream software for the virtual prototype system, combines multi-body dynamics modeling with large displacements as well as multi functioning tools. It also supports data exchange with other geometric modeling software during product development. This software has more powerful geometric modeling function. Due to this a kinematics model of tentacle robot propulsor is designed in Figure 2 and further imported into Matlab through a common data exchange interface with .XML format. Designed tentacle parameters are as below:
Table 1. Identified Link Parameters of Tentacle Robot Model.

| i  | \( a_i \) (link length) | \( m_i \) (link weight) | \( d_i \) (link offset) | \( \theta_i \) (joint angle) |
|----|-------------------------|-------------------------|-------------------------|---------------------------|
| 1  | 15.89cm                 | 0.587kg                 | \( d_1 = 0 \)           | \( \theta_1 \)            |
| 2  | 15.68cm                 | 0.281kg                 | \( d_2 = 0 \)           | \( \theta_2 \)            |
| 3  | 15.68cm                 | 0.281kg                 | \( d_3 = 0 \)           | \( \theta_3 \)            |
| 4  | 15.68cm                 | 0.281kg                 | \( d_4 = 0 \)           | \( \theta_4 \)            |
| 5  | 15.68cm                 | 0.281kg                 | \( d_5 = 0 \)           | \( \theta_5 \)            |
| 6  | 13.9cm                  | 0.570kg                 | \( d_6 = 0 \)           | \( \theta_6 \)            |

Figure 2. CAD design by using Solidworks software.

C. Sim-Mechanics model for the proposed tentacle:

In computer simulation process this tentacle is analyzed for a single joint to identify the respective angle, velocity and acceleration. Once the tentacle robot propulsor model is designed and exported into physical Modeling STL format than a Sim-Mechanics toolbox Model is generated in Simulink.

Figure 3. Simulation model diagram in Simulink in Matlab.

D. Simulink Model

After importing the Solidworks physical model .XML file into the Mathlab using Sim-Mechanics, a Simulink model is build. This model is upgraded to provide the real environmental constrain in integrating the drag co-efficient model in the Simulink model to generate the approximate natural movement to extract to the desired torque for individual joint to achieve the desired motion. This
Simulink model is further modified in considering the drag effect in the normal water. The designed Simulink model is provided below.

![Simulink model diagram of the Designed CAD model for the tentacle.](image1)

**Figure 4.** Simulink model diagram of the Designed CAD model for the tentacle.

For the drag equation, the model is modified and designed accordingly to implement the following equation and applied on the link centre of Gravity (CG) point.

\[
F_D = \frac{1}{2} \rho \theta^2 C_D A
\]

\[
\rho = \frac{m}{v} \left(\text{1000 kg/m}^3\right)
\]

\[
C_D = 1.98
\]

\[
A = \text{Facing area}
\]

Therefore, the designed model appears as of Figure 5:

![Simulink model diagram for the drag equation of the tentacle.](image2)

**Figure 5.** Simulink model diagram for the drag equation of the tentacle.
3. MODEL ANALYSIS
IKS Response is obtained for the first link joint in considering it acting as a driving link and the first joint as the driving joint. Besides that, rest of the joints will is making the sinusoidal movement from the reaction force acting on individual joint. Therefore this simulation aims to acquire the required torque for the driving joint. In the simulation model we achieved the angular position, velocity and acceleration for individual joints and from the graph we can individual joints diagrams are quite unique to each other. Obtained angular position, velocity and acceleration curves are provided below in Figure 6-9.

![Figure 6](image6.png)

**Figure 6.** Base joint angular position vs. time response.

![Figure 7](image7.png)

**Figure 7.** Base joint angular velocity vs. time response.
CONCLUSION AND FUTURE WORKS

This paper describes the modelling method of a Bio-Inspired tentacle robot to achieve the propulsion in underwater. Simulation provides the feasibility of the tentacle robot and through the simulation we achieve the driving joint manipulators angular, velocity and acceleration with respect to the time which can be applied in the real prototype once the prototype designed and simulated to mimic the simulation design. Simulation has been carried out to identify the required torque for the experimental design. This works describes a method and steps to build a simulation model from a CAD model to a simulation model and evaluates the simulation results to justify the acquired results. A real prototype will be designed for further improvement on this study.
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