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Role of Smart Actuators and Smart Sensors in the Design of underwater Mobile Manipulators

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***Abstract*— Mobile manipulators have been used in applications such as material transport and industrial automation system. Mobile manipulator consists of a mobile base and a manipulator. The role of mobile platform of the manipulator is to position the moving platform in a desired configuration. Mobile manipulators are needed for underwater intercede missions such as inspection, contact type, welding, closing/opening/partially closing or opening of the valves. Underwater mobile manipulators are limited to closed type applications and are attached to submerged vehicles that are continuously moving. Therefore it is very difficult to operate accurately these underwater mobile manipulators. Concerned with kinematic analysis of underwater mobile manipulator is to studying the motion without considering the forces that causes the motion. The main goal of the kinematic analysis of the underwater mobile manipulator is to determine the position, velocity and acceleration of the moving platform as a result of given prescribed input motions. Increasing the stability of underwater mobile manipulators, several smart materials, smart actuators and sensors are to be used to sense and react to the effect of environmental inputs, and to stimulate the devices. The number of actuators, sensors and other devices of the underwater mobile manipulators such as mobile platform, limbs and joints have been developed based on smart material technologies which are basically very small version in size and light in weight. The actuators have to be developed from smart materials, such as Shape Memory Alloy and Electro Active Polymers which are very much suitable for the design of underwater mobile manipulators. The characteristics of these smart materials are that they have the ability to return to their original shape even after several deformations. This paper presents the benefits for using the smart actuators, smart sensors for the design of underwater mobile manipulators to provide greater mobility and stability.**

***Keywords*— smart actuators, smart sensors, underwater mobile manipulators, Mobility, stability, kinematic analysis and dynamic analysis**

I. INTRODUCTION

The modelling of underwater mobile manipulators, are different from that of land robots. In land manipulators base was fixed, but in the case of underwater mobile manipulators the base is not fixed. In this paper the kinematic and dynamic equations of motion of underwater mobile manipulator are to be derived. The performance criteria of the dynamic response of the manipulators are to be controlled by the controller of the underwater mobile manipulator. The dynamic equations of the control structure of the underwater mobile manipulators depends on the formation of torque, friction, inertia couple, displacement, velocity, acceleration, coriolis acceleration, external force, centripetal force, effect of gravity, buoyancy force, kinematic analysis and its trajectory planning for a given task and precision space input. Underwater mobile manipulators should be able to sense the obstacles and modify its path to avoid obstacles by R Siegwart, J yah [13, 17] are finding applications. The variety of micro intelligent sensors, open and closed loop real time control algorithms are used in underwater mobile manipulators. The wise variety electronic devices such as actuators, sensors, and and modify its path to avoid obstacles by R Siegwart, J yah [13, 17] are finding applications. The variety of micro intelligent sensors, open and closed loop real time control algorithms are used in underwater mobile manipulators. The wise variety electronic devices such as actuators, sensors, and controllers are to be used for optimizing the performance of various mechanical components of the selected systems. The micro-controller unit is put together around a central processing unit as the sensors such as displacement, velocity and acceleration sensors are to be used for monitoring the selected system parameters.

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The signals from electronic smart sensors are to be amplified and converted into digital format by using interfacing electronic devices. The collected data are to be processed in micro-controller unit by using control algorithms, which are written by using kinematic equations and also depends on its dynamic action. The velocities of various points on underwater mobile manipulators are to be described by using the Jacobian matrices. Afterword the dynamics of underwater mobile manipulator are to be carried out. There is a rapid growth in the use of smart materials, structures and systems in the current day engineering technology due to their advantages and intelligent features, because these materials that sense and react to the effect of environmental inputs and to stimulate the devices. Several smart materials such as shape memory alloys by *Molfino,* M *Singaperumal,* S *Usha, T Nagarajan* [3, 4, 9, 10] are finding increasing applications. The characteristic of these smart materials is that they have the ability to return to their original shape even after several deformations. The shape memory alloys are the metals that can be deformed and then returned to their original shape. The most effective and widely used alloys to improve its material properties such as ductility, high fatigue life and corrosion resistance, because NiTinol by *M Sreekumar, Y S Kim and S Miyazaki* [6,12] are discussed and these smart materials possess a peculiar and unique constitutive behaviour, which strongly depends on the effect of loading and operating conditions. It has the ability to remember its initial shape even after subjected to several deformations and these materials restores to its original condition. The applications of smart materials cover areas such as automobile components discussed by *Westergaard* [11], telecommunications, aerospace, structures, underwater mobile manipulators and medical field applications. The actuators developed from smart materials, such as Shape Memory Alloy by by M Sreekumar, S Muthuswamy and M Zoppi [5, 8] and Electro-Active Polymers by *Sait Usha* [7], are very much suitable for underwater mobile manipulators. When high frequency actuation is required in underwater mobile manipulators, the response of Shape Memory Alloy actuators such as piezoelectric material becomes very much suitable, but the strain produced is very low as compared to and Electro-Active Polymers.

II. KINEMATIC ANALYSIS OF THE UNDERWATER MOBILE MANIPULATOR

The kinematic analysis of underwater mobile manipulator is to studying the motion without considering the forces that causes the motion. The main goal of the kinematic analysis of the underwater mobile manipulator is to determine the position, velocity and acceleration of the moving platform as a result of given prescribed input motions. Let, an arbitrary point on underwater mobile platform (a_i), the transportation matrix (A_i), the local position vector of the arbitrary point(a_i) is $\left(P_{a_i}\right)$, the global position vector of arbitrary point (a_i) in a fixed coordinate system can be written as $b_{a_i} = b_i + A_i P_{a_i}$ where b_i is the global position vector of local coordinate system.

The absolute velocity of arbitrary point on underwater mobile platform (a_i) with respect to global reference frame be written as $\dot{b}_{a_i} = \dot{b}_i + \dot{A}_i P_{a_i} + A_i \dot{P}_{a_i}$, similarly the absolute acceleration of arbitrary point on underwater mobile platform (a_i) with respect to global reference frame be written as $\ddot{b}_{a_i} = \ddot{b}_i + \ddot{A}_i P_{a_i} + 2\dot{A}_i \dot{P}_{a_i} + A_i \ddot{P}_{a_i}$

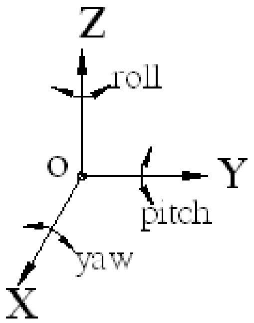
III. DYNAMIC ANALYSIS OF THE UNDERWATER MOBILE MANIPULATOR

The dynamic equations of underwater mobile manipulator are complex and non-linear. Let, generalized coordinate system for the underwater mobile manipulator written as $x = \{x_u, x_v, x_w\}$, transformation matrix A(x), centripetal vector matrix C(x), coriolis vector matrix C_c(x), inertia vector M(x), gravitational vector G(x), buoyancy vector M_b(x), joint friction vector f(x), external force vector F(x), control input parameters x_i.

The dynamic equations of the underwater mobile manipulator are

$$M(x)\ddot{x} + C(x)\dot{x} + Cc(x)\dot{x} + f(x)\dot{x} + G(x) + M_b(x) = F(x) + x_i$$

The position analysis of a moving platform with respect to fixed base platform centre O {x, y, z} can be described by direction cosine representation followed Euler angle representation



Let us consider 3-Euler angles that are

$\emptyset_i$ = rotating about Z-axis of fixed reference frame
θ_i = rotating about Y-axis of fixed reference frame
Ψ_i = rotating about X-axis of fixed reference frame

The 3-Euler angles rotating about Z-X-Y axis of the fixed reference frame in sequence then

$$Euler(\emptyset_i, \Psi_i, \theta_i) = Rot(y, \theta_i) Rot(x, \Psi_i) Rot(z, \emptyset_i) = \begin{bmatrix} c\theta_i c\emptyset_i + s\Psi_i s\theta_i s\emptyset_i & -c\theta_i s\emptyset_i + s\Psi_i s\theta_i c\emptyset_i & s\theta_i c\Psi_i \\ c\Psi_i s\emptyset_i & c\Psi_i c\emptyset_i & -s\Psi_i \\ -s\theta_i c\emptyset_i + s\Psi_i c\theta_i s\emptyset_i & s\theta_i s\emptyset_i + s\Psi_i c\theta_i c\emptyset_i & c\theta_i c\Psi_i \end{bmatrix}$$

Velocity of underwater mobile platform position vector with respect to fixed reference frame are given as J(**x**) where $\boldsymbol{x} = [x\ y\ z\ u\ v\ w]^{\boldsymbol{T}}$

$$J = \begin{bmatrix} c\theta_i c\emptyset_i + s\Psi_i s\theta_i s\emptyset_i & -c\theta_i s\emptyset_i + s\Psi_i s\theta_i c\emptyset_i & s\theta_i c\Psi_i & 0 & 0 & 0 \\ c\Psi_i s\emptyset_i & c\Psi_i c\emptyset_i & -s\Psi_i & 0 & 0 & 0 \\ -s\theta_i c\emptyset_i + s\Psi_i c\theta_i s\emptyset_i & s\theta_i s\emptyset_i + s\Psi_i c\theta_i c\emptyset_i & c\theta_i c\Psi_i & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & c\emptyset_i & -s\emptyset_i \\ 0 & 0 & 0 & 0 & s\emptyset_i & c\emptyset_i \end{bmatrix}$$

Inertia vector

$$M(x) = \begin{bmatrix} x_{\dot{x}} & x_{\dot{y}} & x_{\dot{z}} & x_{\dot{u}} & x_{\dot{v}} & x_{\dot{w}} \\ y_{\dot{x}} & y_{\dot{y}} & y_{\dot{z}} & y_{\dot{u}} & y_{\dot{v}} & y_{\dot{w}} \\ z_{\dot{x}} & z_{\dot{y}} & z_{\dot{z}} & z_{\dot{u}} & z_{\dot{v}} & z_{\dot{w}} \\ u_{\dot{x}} & u_{\dot{y}} & u_{\dot{z}} & u_{\dot{u}} & u_{\dot{v}} & u_{\dot{w}} \\ v_{\dot{x}} & v_{\dot{y}} & v_{\dot{z}} & v_{\dot{u}} & v_{\dot{v}} & v_{\dot{w}} \\ w_{\dot{x}} & w_{\dot{y}} & w_{\dot{z}} & w_{\dot{u}} & w_{\dot{v}} & w_{\dot{w}} \end{bmatrix}$$

The coriolis matrix in the style of

$$(x) = \begin{bmatrix} 0 & 0 & 0 & 0 & -m_z & m_y \\ 0 & 0 & 0 & m_z & 0 & -m_x \\ 0 & 0 & 0 & -m_y & m_x & 0 \\ 0 & -m_z & m_y & 0 & -m_w & m_v \\ m_z & 0 & -m_x & m_w & 0 & -m_u \\ -m_y & m_x & 0 & -m_v & m_u & 0 \end{bmatrix}$$

Where

$$\begin{bmatrix} m_x \\ m_y \\ m_z \\ m_u \\ m_v \\ m_w \end{bmatrix} = \begin{bmatrix} x_{\dot{x}} & x_{\dot{y}} & x_{\dot{z}} & x_{\dot{u}} & x_{\dot{v}} & x_{\dot{w}} \\ y_{\dot{x}} & y_{\dot{y}} & y_{\dot{z}} & y_{\dot{u}} & y_{\dot{v}} & y_{\dot{w}} \\ z_{\dot{x}} & z_{\dot{y}} & z_{\dot{z}} & z_{\dot{u}} & z_{\dot{v}} & z_{\dot{w}} \\ u_{\dot{x}} & u_{\dot{y}} & u_{\dot{z}} & u_{\dot{u}} & u_{\dot{v}} & u_{\dot{w}} \\ v_{\dot{x}} & v_{\dot{y}} & v_{\dot{z}} & v_{\dot{u}} & v_{\dot{v}} & v_{\dot{w}} \\ w_{\dot{x}} & w_{\dot{y}} & w_{\dot{z}} & w_{\dot{u}} & w_{\dot{v}} & w_{\dot{w}} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ u \\ v \\ w \end{bmatrix}$$

The centripetal vector matrix

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$$C(x) = \begin{bmatrix} 0 & 0 & 0 & 0 & -n_z & n_y \\ 0 & 0 & 0 & n_z & 0 & -n_x \\ 0 & 0 & 0 & -n_y & n_x & 0 \\ 0 & -n_z & n_y & 0 & -n_w & n_v \\ n_z & 0 & -n_x & n_w & 0 & -n_u \\ -n_y & n_x & 0 & -n_v & n_u & 0 \end{bmatrix}$$

Where

$$\begin{bmatrix} n_x \\ n_y \\ n_z \\ n_u \\ n_v \\ n_w \end{bmatrix} = \begin{bmatrix} x_x & x_y & x_z & x_u & x_v & x_w \\ y_x & y_y & y_z & y_u & y_v & y_w \\ z_x & z_y & z_z & z_u & z_v & z_w \\ u_x & u_y & u_z & u_u & u_v & u_w \\ v_x & v_y & v_z & v_u & v_v & v_w \\ w_x & w_y & w_z & w_u & w_v & w_w \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ u \\ v \\ w \end{bmatrix}$$

IV. SMART ACTUATOR

Smart actuators such as shape memory alloy and electro-active polymers are very much suitable actuation capabilities and simultaneous sensing. Smart materials such as piezoelectric and the ability of smart materials are return to some previously defined shape and size when subjected to shape memory effect. The properties of shape memory alloy and electro-active polymers are large recoverable strains, high power density, high tensile strength, good damping properties, high thermal conductivity, good resistance, less sensitiveness to magnetic resonance, crush recoverability and excellent push ability. The most common smart materials in shape memory alloy actuators are NiTinol. The advantages and limitations of shape memory alloy actuators are high power density, large force output per unit weight, large stroke length per weight ratio, large recoverable strain per stroke, electrical actuation at small voltages, rapid motion at a specified temperature, easy to activate, high reliability, verity of shape changes, noise free operation,biocompatibility, compact, light weight, insensitive to wide variety of environmental condition.

The characteristics of shape memory alloy actuators such as one way shape memory, two- way shape memory, super elasticity made them suitable for a specific application. In general, for the use of shape memory alloy actuator in underwater mobile manipulator, the important factors to be considered while designing a system actuated by shape memory alloy are the shape of the actuator, bias force required for deforming the actuator, type of fixing the actuator with the structure, type of control system to be adopted for actuation and sensors being incorporated to measure the parameters like positions, velocity, acceleration, temperature, force and resistance. The one way shape memory effect of smart material has soft, ductile and easily deformable in its lower temperature form with the application of an external force. The two way shape memory effect the ability of shape memory alloy to recover a present shape and return to the same shape without the influence of any external force, means it is associated with a shape change without requiring any external bias force, and the super elasticity of shape memory alloy has highly elastic, quite strong and hard. The selection of a particular form of the actuator for a specific task is based on strain, bias force, actuation force, torque and frequency of operation.

The thin film of Nitinol is another form of shape memory alloy actuator used in thin film Nitinol on off valves. The various forms of shape memory alloy actuators for underwater mobile manipulators, such as linear actuators, spring actuators, rotary actuators, bundle actuators. The response of shape memory alloy actuators mainly depends upon the type of controllers incorporated and the way in which the phase transformation. The number of cooling techniques are like water immersion, heat sinking, forced air or liquid cooling, still air or cools chips technique are available to reduce the cooling time of the actuator. The smart materials of electro-active polymer actuators are activated by electrically induced transport of ions, molecules and electrostatic forces developed due to electric field.

The smart material that shrinks under electrical activation, consequently increasing in area on other directions of the device and produce required tensile strain can be optimized for better activation effects. The actuators are fabricated with many thin layers of dielectric electro-active polymer films that are coated with silver electrodes. The strain produced with these actuators based on elastic stiffness and dielectric constants of electro-active polymer materials. The smart actuators works on the principal that opposite charges attract and like charges repel each other. The smart dielectric material is basically sandwiched between two complaint electrodes. When power is applied to smart dielectric electro-active polymer material, then stress is induced by electrostatic attraction, and this stress causes smart material to get compressed in the thickness and its area increases. The typical electro-active polymer materials are conductive, conjugated, piezoelectric ferroelectric, polymers and dielectric electro-active polymers.

V. SMART SENSOR

The inverse process of actuation makes the dielectric electro-active polymer material to work as the sensor. When force or pressure is applied on dielectric electro-active polymer, it changes its role and act as a sensor. The input force or pressure on smart dielectric electro-active polymer material, make its capacitance vary and the corresponding effect produces an equivalent electrical output in terms of current or voltage. The different levels of sensor integration with signal processing circuit as shown in figure 1.

The smart sensor offers a solution by integrating the sensor and necessary signal conditioning unit on a single package or on a single silicon wafer. The smart sensor is also posses signal processing capability and have a built in analog to digital converter, microcontroller and memory. The typical smart sensor functional block diagram is as shown in figure 2.

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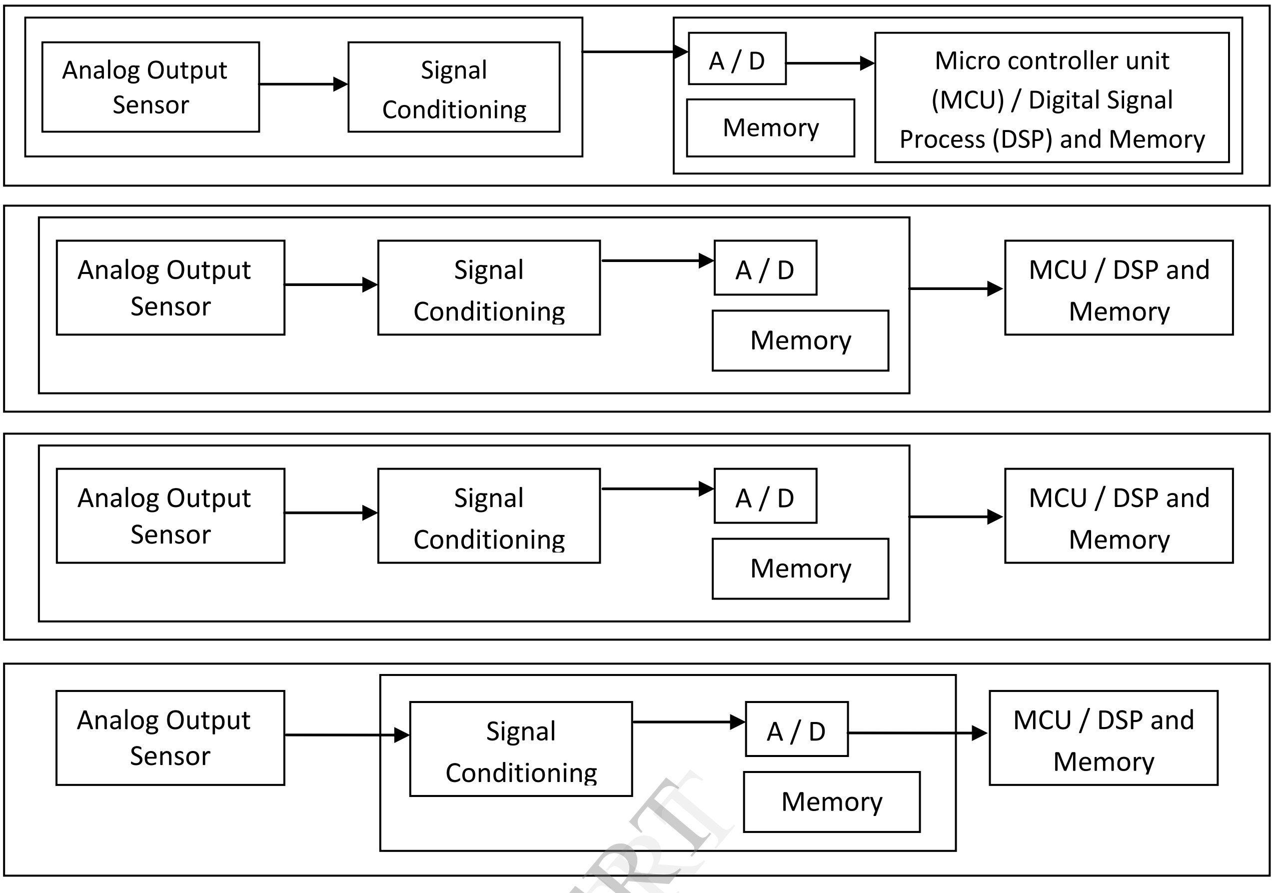

Figure 1: Varies Levels of Sensor integration with signal processing circuit

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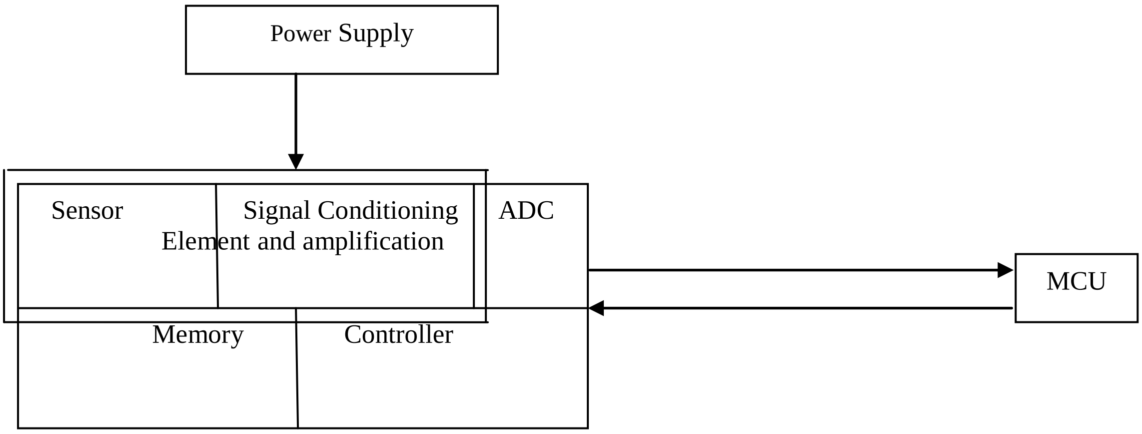

Figure 2: Smart Sensor’s functional Block Diagram

VI. CONCLUSIONS

Due to increase the mobility of the underwater mobile manipulator is to play a major role in underwater applications. The kinematic and dynamic analysis of the underwater mobile manipulator is to understand the complexity of the modelling of the selected system and also to make better design and control of the underwater mobile manipulators. In this paper the steps involved in deriving the kinematic equations of motions have been explained in detail. The dynamic equations of underwater mobile manipulator are complex and non-linear. Efficient actuators and smart sensors are to be used to improve its accuracy, operational speed, flexibility in operation, power consumption and its conditions. An overview and working principle along with a few applications of smart materials are discussed in this paper. The characteristics of these smart materials are that they have the ability to return to their original shape even after several deformations. Smart materials have good mechanical properties such as ductility, high fatigue life, corrosion resistance, light weight and easy to activate. The actuators have to be developed from smart materials, such as Shape Memory Alloy and Electro Active Polymers are very much suitable for underwater mobile manipulator applications due to the development of large strain and actuation force.

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