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Joint Control of a TRRLR Mobile Manipulator for Unstructured Terrain

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ABSTRACT

A mobile manipulator which is combination of a mobile platform and a manipulator, provides a highly flexible system, which can be used in hazardous application. One of the challenges with mobile manipulators is the construction of control systems, enabling the robot to operate safely in potentially dynamic and all terrain environments. In this paper we will present work in which a mobile manipulator is controlled using the hybrid approach. The method presented is a real time approach in which inverse kinematics of the arm with onboard sensor data processing are used both for the overall coordination of the mobile platform and the manipulator as well as the lower level fusion of obstacle avoidance and target acquisition behaviors.

Keywords: Inverse kinematics, IMU, accelerometers, hybrid control

1. INTRODUCTION

Mobile manipulator systems comprised of a mobile platform with one or more manipulators are of great interest in number of applications. This paper presents a planning and control methodology for such systems allowing them to follow simultaneously desired end-effector and platform trajectories without violating the nonholonomic constraints. Robotic manipulators are being considered for a wide variety of applications outside of their traditional factory settings. These applications, such as fire-fighting, toxic waste cleanup, hazardous explosive material handling and planetary exploration will require the manipulators to operate from moving vehicles, as mobile manipulators. A mobile manipulator, composed of a manipulator arm mounted on a mobile platform, is far more versatile than a conventional manipulator whose base is fixed, as a consequence of its enlarged operational space. Typically, a mobile manipulator's vehicle will have significant dynamic behavior, particularly due to suspension compliance, in contrast to factory manipulators generally mounted on rigid bases. As a result, a mobile manipulator's motions will dynamically interact with those of its vehicle on its suspension to degrade the manipulator's performance. Such problems as excessive end-effector errors and poor system stability can result. The control problems for these systems are further exacerbated by highly variable system characteristics. Hybrid approach is a technique combining the kinematic model of the manipulator and sensor data of platform disturbances with real time closed loop control system..

This paper, describes the construction of TRRLR mobile manipulator for uneven and unknown terrain application. Precise control is required to deploy the arm for hazardous mission from folding condition to the mission position. During the mission it is mandatory to maintain a constant gap between the ground and sensor intended to carry out the mission. Then, it represents the kinematics of the system and also the envelope of the manipulator without disturbing the other system. It also discusses about the control scheme of manipulator for real time and unmanned operation on unstructured terrain through the hybrid concept based control.

Stability control of large end point errors caused by dynamic interaction between a mobile manipulator and its platform using limited sensory data in highly unstructured field environments is very vital one [1], two level approach in which competitive dynamics are used both for the overall coordination of the mobile platform and the manipulator as well as the lower level fusion of obstacle avoidance and target acquisition behaviors[2], possibility of synthesizing (smooth) feedback controllers capable of making the nonholonomic platform maneuver automatically in order to perform the manipulation task while avoiding collisions with joint-limits[3], based on kinematics specification of trajectories for both the platform and the end-effector and computation of actuator commands is discussed and orthogonal complements and the Lagrangian methodology were used to obtain the reduced equations of motion for the differentially-driven system[. Based on these equations, a model-based controller was designed to eliminate tracking errors[4]. With inverse kinematics principle, a method to control the servo angles of all arm joints to get the desired tip position is discussed[5].

2. SYSTEM DESCRIPTION AND METHODOLOGY

2.1 Unmanned system with mobile manipulator

Unmanned tracked vehicle carrying mine detection sensors fitted on robotic arm controlled from a base station must posses automatic control and tele operation control to successfully complete the mission. The combined two serial arms has to carry the mine detection sensor which is meant to detect buried land mines in unstructured and unknown terrain. It has to be deployed from the frontal edge of the vehicle with adequate standoff distance from the hazardous objects. The manipulator arm has to maintain the constant distance in between the ground surface and mine detection sensorfor different orientation of the vehicle and sensor together or separately during the movement of the vehicle on undulated terrain. Precise control is required to protect the expensive sensor from obstacles in the path of unmanned vehicle which carries the robotic arm with sensor

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2.2 Methodology

There are two serial arm manipulator fitted in front of the unmanned tracked vehicle. The remote vehicle is controlled from a base vehicle through wireless LAN. The manipulator arms will carry the sensor to detect the buried object under the ground is also remotely operated. But the closed loop control of the end effectors position has to be carried out by an electronic controller system. The suitable control loop to carry out the position control based on the signals from onboard sensors like ultrasonic distance sensors, Inertial Measurement Unit and array of accelerometer will reside in the embedded controller. The each arm has five degree of freedom such as base turret twist (T), back arm rotation (R), fore arm rotation (R), fore arm linear actuation (L) and rotation of end effectors (R). The configuration of this arm is TRRLR and is represented in Figure.1

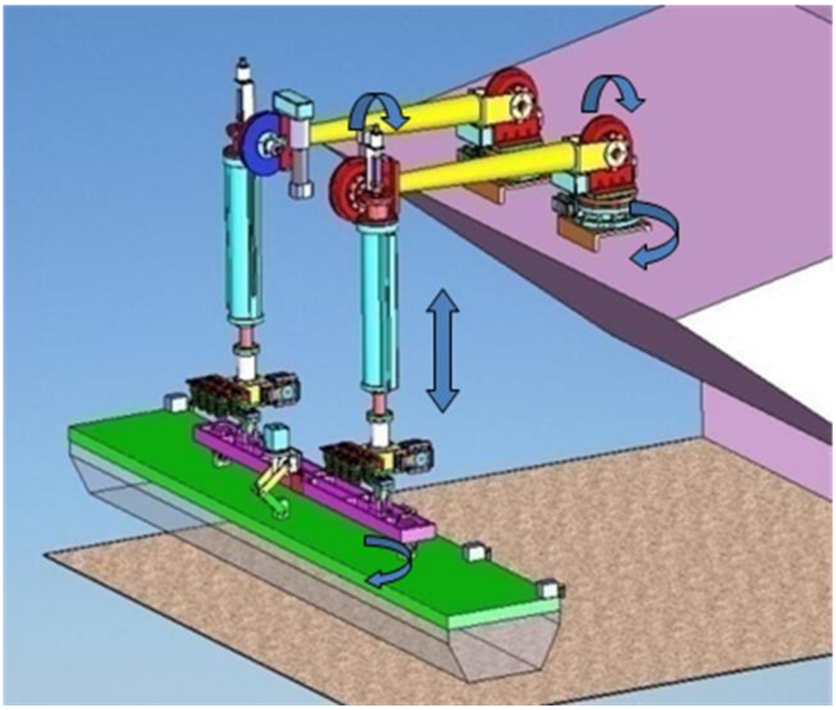

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Figure 1 TRRLR mobile manipulator arms with sensor

The gap between the ground surface and the sensor is maintained by measuring the distance with ultrasonic sensors. The vehicle pitch, roll is measured by means of onboard Inertial Measurement Unit and that of arm with sensor is by means of accelerometers. The measured data is used to ensure mine detection sensor to orient itself to the undulations of ground and different orientation of the vehicle through a real time hybrid controller embedded with inverse kinematics of the robotic arm in constrained conditions. The arm with sensor will travel in a suitable trajectory based on laser based obstacle detection system data to protect the sensor from damages during unmanned operation. The acoustic sensors are mounted in the form of arrays with known distance. The depths from the different sensors are analyzed by finding the inclination angle α and Φ in the plane of roll and pitch as shown in Figure 2. Based on these results the corresponding joint actuators are rotated to make the mine detection sensor optimally parallel to the ground undulations. The inverse and forward kinematic analysis of the arm is the utilized to ensure the safety of the sensor mounted on the arm from unknown terrain obstacle when the unmanned vehicle is deployed for the mine detection mission. The fig 3 shows the required dexterity of the end effectors mounted with the sensor. Obstacle detection sensor is mounted on the frame carried by the robotic arm along with the sensor

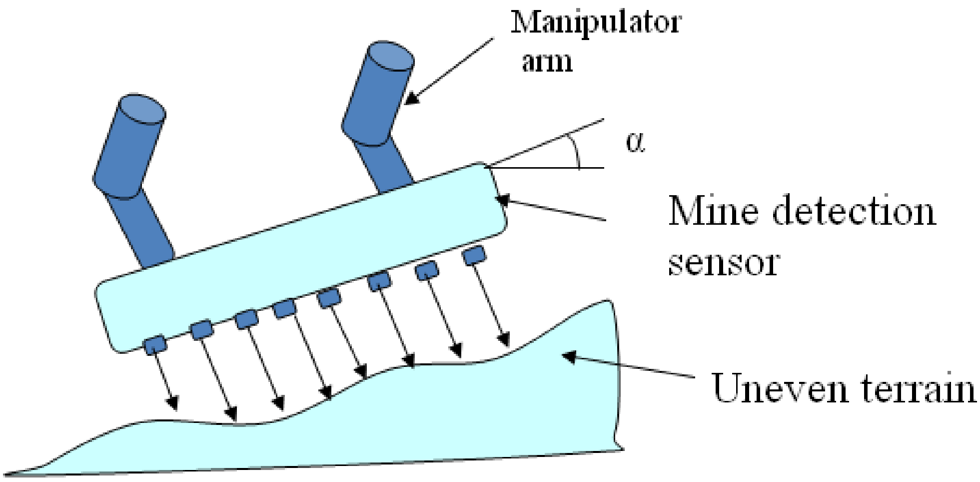

Figure 2 Measurement of unevenness of the ground

3. KINEMATICS OF THE MANIPULATOR

3.1 Forward Kinematics

In manipulator system, five Degree of freedom jointed arm configuration Twist-Revolute-Revolute-Linear-Revolute (TRRLR) is designed to carry the sensor and marking unit at the end effectors. The forwarded kinematics of the single arm is represented as below in fig 4. The Denavit - Hartenberg parameters [8] have been worked out for this configuration as shown in table 1. It represents the link parameters like link rotation θi, link length ai, link twist αi and link offset di

TABLE 1: D-H PARAMETERS OF MANIPULATOR

Joint	θ_i	α_i	a_i	d_i
1	θ_1	90	0	0
2	θ_2	0	a_2	0
3	θ_3	90	0	0
4	θ_4	0	0	d_4
5	θ_5	0	a_5	0

By multiplying sequentially the transformation matrices from the initial frame to the end-effectors frame. The transform matrix for the four joint as arrived in equation 1 to 6

$$T5^{0} = T1^{0}\, T2^{1}\, T3^{2}\, T4^{3}\, T5^{4} \tag{1}$$

$$T1^{0} = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & a_1\cos\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 & a_1\sin\theta_1 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T2^{1} = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 & a_2\cos\theta_2 \\ \sin\theta_2 & 0 & -\cos\theta_2 & a_2\sin\theta_2 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T3^{2} = \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 & a_3\cos\theta_3 \\ \sin\theta_3 & 0 & -\cos\theta_3 & a_3\sin\theta_3 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$T4^{3} = \begin{bmatrix} 1 & 0 & 0 & a_4 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$T5^{4} = \begin{bmatrix} \cos\theta_5 & 0 & \sin\theta_5 & a_5\cos\theta_5 \\ \sin\theta_5 & 0 & -\cos\theta_5 & a_5\sin\theta_5 \\ 0 & 1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

The position of the end effector is found after multiplying the above matrices and is given in the following equations

$$X = d_5 \sin(\theta_1) + \cos(\theta_1)(a_2 \cos(\theta_2) + d_4 \sin(\theta_2+\theta_3)) \quad (7)$$

$$Y = -d_5 \cos(\theta_1) + \sin(\theta_1)(a_2 \cos(\theta_2) + a_5 \cos(\theta_2+\theta_3+\theta_5) + d_4 \sin(\theta_2+\theta_3)) \quad (8)$$

$$Z = -d_4 \cos(\theta_2+\theta_3) + a_5 \sin(\theta_2+\theta_3+\theta_5) \quad (9)$$

The ADAMS simulation of single arm is shown below. Single arm forward kinematics analysis using ADAMS simulation is shown as in Figure 3 and 4.

Figure 3. Initial position of joints in simulation

Figure 4. Intermediate position of joints in simulation

The position of each link can be continuously monitored by the respective encoder in each joint and the data acquired from the IMU and accelerometer fed to the manipulator controller will facilitate to control the corresponding actuator accurately with the help of inverse kinematic analysis.

3.2 Inverse Kinematics

It is essential to move the mine detection sensor in the straight line like moving the sensor only in x direction alone and similarly, move the sensor only in z direction. It can be achieved by means of the inverse kinematics that the angle of the manipulators will be arriving. It is possible to dictate the manipulator movement in a straight line by specifying the x, y and z distance. Once the final target is known, further work out the angle of rotation for rotary joints and displacement for linear joints are arriving by means of the inverse kinematics as shown in eqn (5), (6) and (7)

$$d_4 = \sqrt{(p_x^2 + p_y^2 + p_z^2)} \tag{10}$$

$$\theta_3 = \cos^{-1}(p_z / d_4) \tag{11}$$

$$\sin\theta_1 = (p_y - d_4 \sin\theta_3) / a_2 \cos\theta_3 \tag{12}$$

$$\cos\theta_1 = (p_x - d_4 \sin\theta_3) / a_2 \cos\theta_3 \tag{13}$$

$$\theta_1 = A\tan^{-1}(\sin\theta_1 / \cos\theta_1) \tag{14}$$

4. DYNAMICS OF MANIPULATOR ARM

Accounting for robot dynamics is necessary to sizing the link depends on the loads that must be supported by the link, including actuators, sensor load, and forces applied by other links. Here, a Newton–Euler formulation is used to write the full spatial dynamics of the system. The torque and force at the base of the manipulator is the cumulative effect from the end effectors. The schematic diagram of the manipulator dynamics is shown in Figure 5. The maximum torque occurs when the arm is extended to maximum stroke length of the prismatic joint as in Figure 6

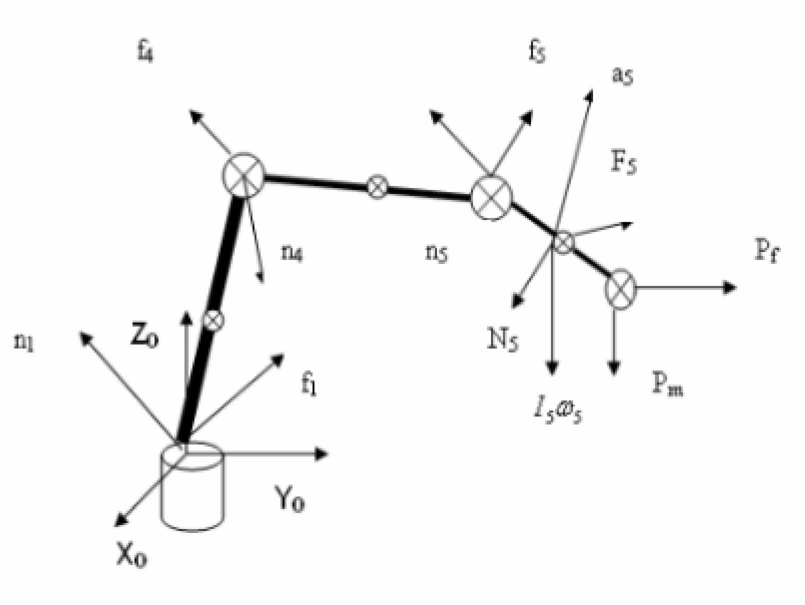

Figure 5 Manipulator Dynamics

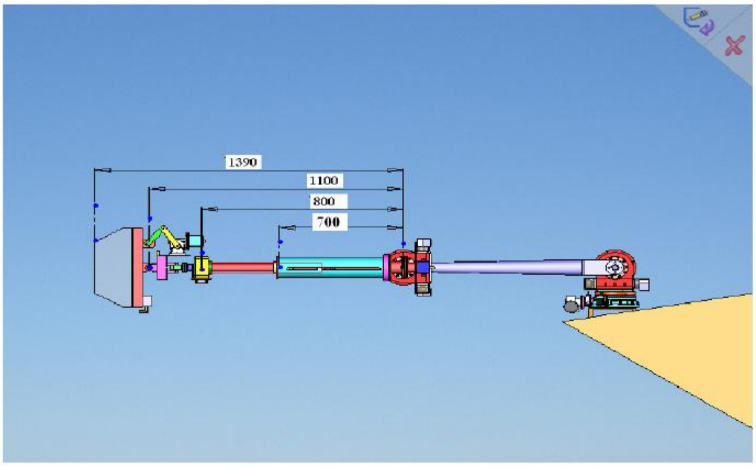

Figure 6 Maximum torque requirement condition

5. MANIPULATOR ARM CONTROLLER

The manipulator arm controller is designed as rugged unit with three main boards and a customized back plane. The following three boards are inserted In to the customized back plane viz., Sensor Interface board,. CAN and Stepper board, MPC 8640 or 8548 based Single Board Computer. The following fig 9 gives the system block diagram of the complete proposed system. The system shall be divided in to three sections. Remote vehicle sub systems, Base vehicle sub systems and control console unit. The manipulator controller is the master control unit present in the Remote vehicle. The

SBC receives and sends data with the RV payload controller (not under scope of this Project) via Ethernet communication. It communicates with the sensor interface board and CAN & stepper Board through two dedicated Ethernet connections. Sensor interface board Converts the ±4V analog voltage from 6 Accelerometers into digital using the Analog to digital convertor, and acquires the digital data in FPGA. The accelerometer gives the output analog in X, Y, Z three axes. The sensor interface board converts the analog signals in a desired sequence and stores the complete data. Once data from all the 18 channels are acquired and saved in to the FPGA the board sends a interrupt to the SBC 8640 board. When the interrupt is received the SBC will read the data from the FPGA. It Monitors the Inertial measurement unit using RS422 (Yaw, Pitch & Roll). The Yaw, Pitch & Roll are received from the IMU. Sensor interface board receives the data from the IMU through serial communication link and sends the data to the SBC 8640.

The CAN and Stepper Card designed for implementing two independent CAN bus interfaces for connecting five MCUs and 10 Absolute Encoders in motion controller for manipulator arm control unit. Main functionality of this card is to receive the commands from the MPC8640 CPU of Single Board Computer (SBC) connected through the Backplane Connectors and transfer the same commands to the MCU of Servo Motors. Hence the CAN and Stepper Card acts as a Communication controller to the SBC and MCU of Servo Motors. It also receives the feedback data from the absolute encoder via CAN bus and send them to the SBC. Since the speed of the CAN bus is 1Mbps the Ethernet communication between SBC and this board is 10/100Mbps. The 5 MCU of Servo motors are interfaced through 2 CAN Bus Channels with each channel supporting speed of 1 Mbps. The individual motor is controlled using hybrid concept with embedded ARM9 microcontroller H/W and embedded ‘C’ S/W. The motor controller unit block diagram is as in fig 10. The Motor Control Unit (MCU) system is designed based on ARM 9 core LPC2917 Microcontrollers. The unit consists of two LPC2917 micro controllers and each controlling one motor unit. Both processors are running simultaneously for redundancy purpose. The each controller having two CAN Bus interface with Vehicle Control Unit (VCU) for redundant communication. Any one of the microcontroller is in failure condition the other one taking the additional load of controlling two motors. Any failure conditions the VCU command the active micro controller to take up the additional load. The sensors and gate driving circuits are isolated with the digital circuits. The appropriate MOSFETs (FDP3632) are selected depends on driving requirement of the BLDC motors. The unit is enclosed with rugged chassis with circular connector for CAN Bus communication and other interfaces.

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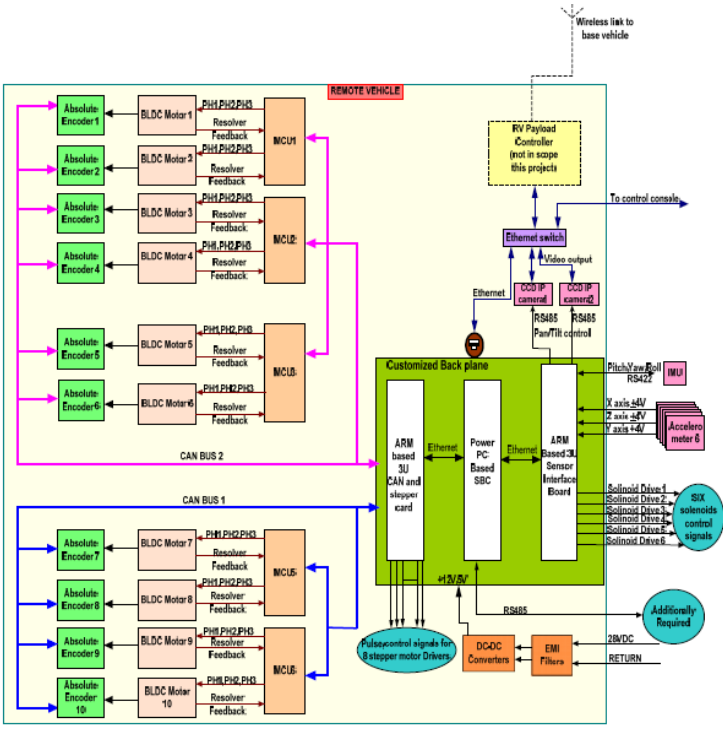

Figure 7 Manipulator arm controller

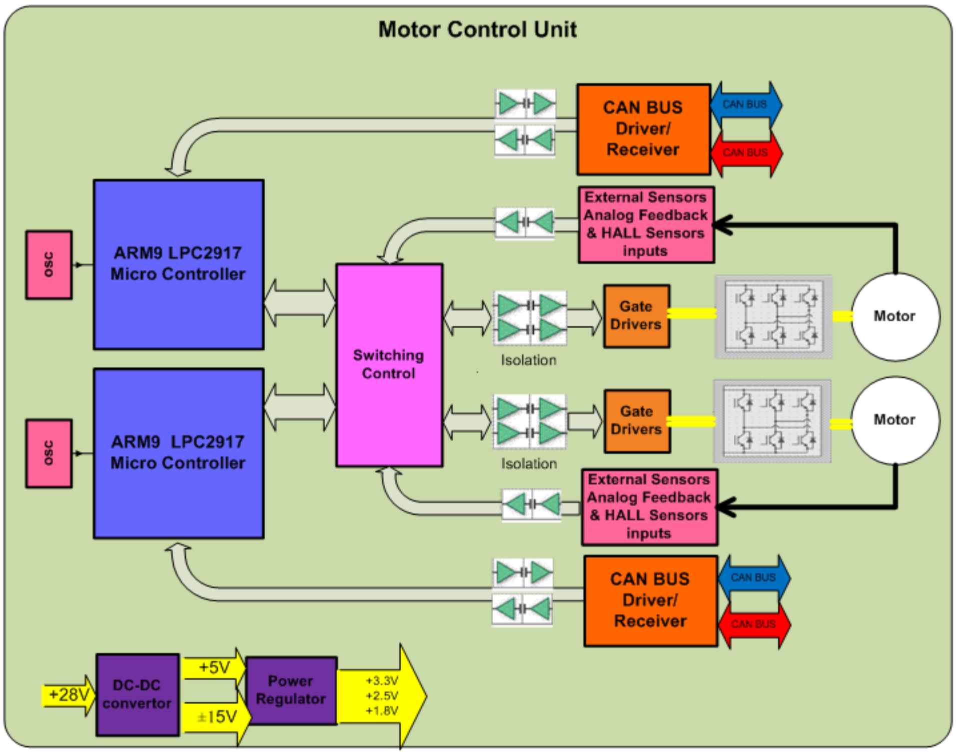

Figure 8 Motor controller unit

6. Results and Discussion

Adams simulation of forward kinematics and closed loop PID control of joint motor is discussed as below. Each arm without any mission constraints designed to meet the following work envelope, Turret : -90deg to +90deg, Back arm : vertical 0deg, 270deg included, Fore arm : vertical 0deg, 270deg included, Linear actuator : 400mm, Rolling : -20deg to +20deg ADAMS simulated results are discussed in the following section

For an angular displacement of 90 deg the peak torque is 110 N-m is noticed. Based on this a suitable rating BLDC motor and servo drive has been integrated and tested for open loop performance. Positional data of motor is obtained through resolver. That analog signal is converted to digital (16 bit resolution). Angular value is calculated using the formula, Resolver_angle = (digitaldata* 360))/65536. Direction of motor rotation is achieved by PWM firing sequence. Angular displacement θ. of the manipulator joint is controlled in conjunction of absolute encoder and resolver feedback signals. PWM frequency determines the switching from one phase to another of the rotor winding. Duty cycle of the PWM determines the speed of rotation of the motor through PID loop. The rise, cruise and fall time of PWM duty cycle are controlled with absolute encoder real time feedback signal. Smooth control of each motor is achieved by means of PWM duty cycle through hybridized embedded H/W and S/W with conventional PID loop. Real time control of multiple joint motor control by means of optimized control logic to be implemented.

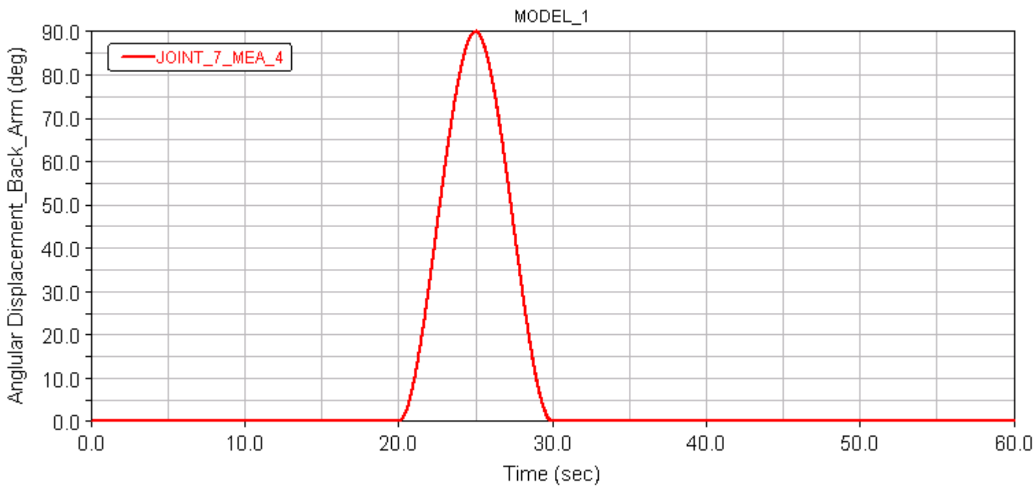

Figure 9 Back arm angular displacement

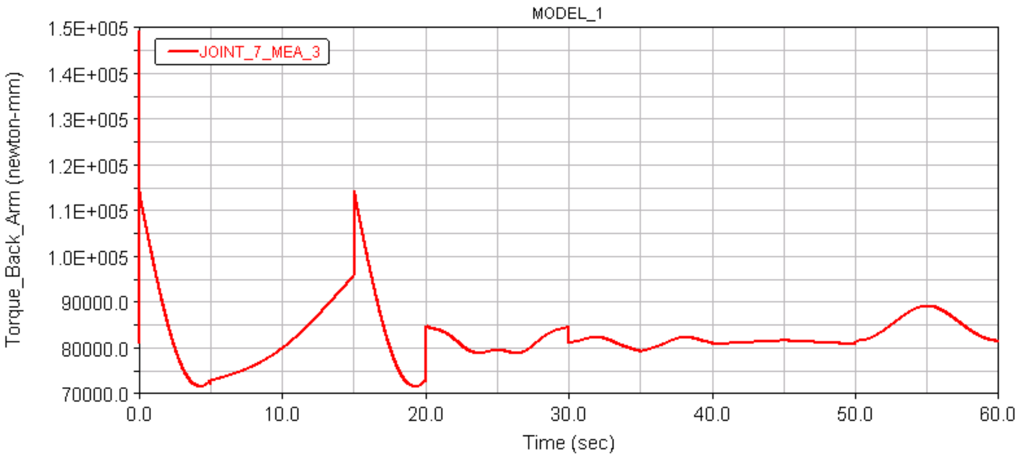

Figure 10 Back arm joint torque

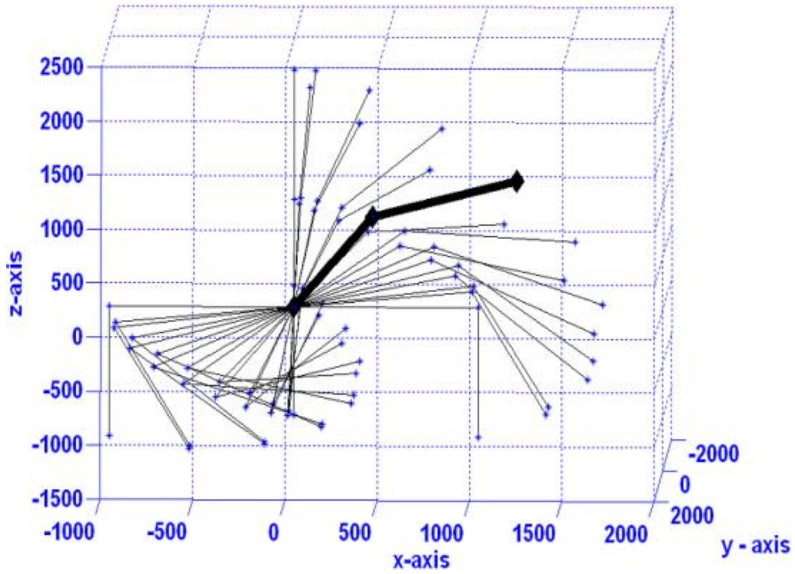

Figure 11 Single arm forward kinematics

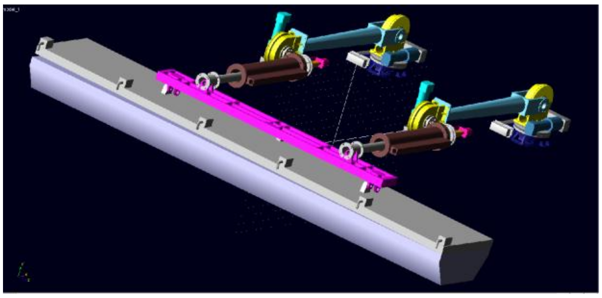

Figure 12. Model of constrained arms with sensor integrated

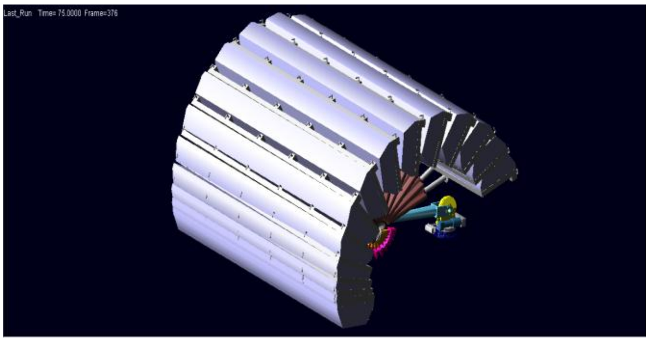

Figure 13. Inverse kinematics constrained model of arms with sensor integrated

7. Conclusion

This paper exhaustively addresses the issues related to the control scheme of the mobile manipulator arm to be used on an unmanned tracked vehicle for carrying out hazardous roles in unstructured terrains. The inverse kinematics of the single arm is used to control the end effector position is discussed. The hybrid concept of embedded system has been used in the manipulator arm joint control along with ADAMS simulation of all joints of single arm and constrains arms with sensor integrated. This scheme has to be implemented for the real time control of the multiple axes of the arm with same hybrid methodology. Different control system methods to be analysed for closed loop precise control of the arm for unstructured environment.

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