THE GEOMETRIC DESIGN OF SPHERICAL MECHANICAL LINKAGES WITH DIFFERENTIAL TASK SPECIFICATIONS: EXPERIMENTAL SET UP AND APPLICATIONS

A Thesis

by

PHANI NEEHAR KAPILA BALA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Mechanical Engineering

The Geometric Design of Spherical Mechanical Linkages with Differential Task

Specifications: Experimental Set Up and Applications

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Approved by:

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ABSTRACT

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(August 2011)

Kapila Bala Phani Neehar, B.Tech., Mahatma Gandhi Institute of Technology, India

Co-Chairs of Advisory Committee: Dr. Nina Robson
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The thesis focuses on the development of an experimental set up for a recently developed failure recovery technique of spatial robot manipulators. Assuming a general configuration of the spatial robot arm, a task is specified. This task contains constraints on position, velocity and acceleration to be satisfied. These constraints are derived from contact and curvature specifications. The technique synthesizes the serial chain and tests if the task can be satisfied in case of a joint failure. An experimental set up was developed in order to validate the failure recovery technique. It includes a robot arm mounted on a movable platform. The arm and platform are controlled by NI sbRIO board and are programmed in LabVIEW. The experimental results of the failure recovery technique for the case of Elbow failure were obtained in Mathematica by fixing the faulty joint at an angle, these results were later tested on the robot arm and platform and satisfaction of task was obtained.

The thesis considers two applications of the synthesis of spherical five –degree-of-freedom serial chains: Power assist for human therapeutic movement and Synthesis of

Parallel Mechanical Linkages. Spherical TS chains have been synthesized for these two applications using the Mathematica software and the mechanisms were able to satisfy the task constraints.

DEDICATION

To my parents, mentors and friends

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First and foremost I would like to acknowledge God for giving me this opportunity and my family members for letting me study the masters degree in the United States. I thank my advisor, Dr. Robson, for guiding me throughout the research and graduate studies. She helped me in many ways to develop myself professionally and academically and by being patient with me in both success and failure of acquiring results.

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1. INTRODUCTION

1.1 Overview

This thesis extends upon recent advancement in the failure recovery analysis, the formulation of a novel synthesis technique by Robson and McCarthy [1], where synthesis techniques for a joint actuator failure recovery of robot manipulators working in remote and challenging environments are proposed. The task for the robot manipulators consist of positions, velocities and accelerations, derived from contact and curvature constraints of the end-effector with the environment [2], The current research develops an experimental set up for testing this synthesis technique. The experimental set up is built in the Space Robotics Laboratory at Texas A&M University, College Station. It requires a rough terrain on which a mobile platform and the robot arm are run.

The applications of the synthesis of spherical serial chains in Power assist mechanism and the design of a closed loop kinematic chains have been also discussed. The synthesis is developed using Mathematica software.

This thesis follows the style of *IEEE Transactions on Automation and Control.*

2. LITERATURE SURVEY

2.1 Geometric Design of Serial Chains with Velocity and Acceleration Specifications

Kinematics is the branch of classical mechanics that describes the motion of bodies (objects) and systems without consideration of the forces that cause the motion. The motion of bodies is basically described by the vectors: Velocity and Acceleration. These velocity and acceleration are the derivatives of the position variable with respect to a reference frame.

A mechanism is a group of rigid bodies connected together to give out a specified force or torque at the end. A robot arm is a series of links joined together at different joints. The motions are possible at these joints bring about relative motion between different links of the robot arm. A serial chain is a combination of different links connected together by joints, specifically, if there are ‘n’ links in a robot arm, there has to be ‘n-1’ joints in a serial chain.

The number of independent variables which has to be specified to specify the net motion of a mechanism is called Degrees of Freedom. In a serial chain; we need ‘n-1’ variables specified to get the sense of output motion. Thus a serial chain with ‘n-1’ joints is said to have ‘n-1’ degrees of freedom.

A robot arm typically has links connected to one another and the end effector connected at the end, the end effector can have a tool, precisely like a gripper to perform different operations. When the end effector is in contact with an object at a particular time, it has to possess a certain velocity normal to the surface of the object to be in contact with it and certain acceleration to be able to slide along that object. When the robot arm with this end effector is to be synthesized, it starts with the designer who provides the information about the velocity and acceleration which are needed at a particular position, for the arm to satisfy the task, then comes the concept of Geometric Design.

This stage of the design process is to synthesize a serial chain. The calculation of geometric parameters of a multiple link robotic or mechanical system so that it guides a rigid body in a number of specified spatial locations is known as the rigid body guidance problem or geometric design problem. These spatial locations are also known as also known as precision points [3]. The precision points differ in relation to the problem, whether it is planar or spatial. In a planar mechanism, we have three precision points: position in X, Y and the angle ‘θ’. In spatial mechanisms we have six precision points: positions in X, Y and Z and angles: Roll, Pitch and Yaw or Longitude, Latitude and Roll given by $\{\theta, \varphi, \psi\}$. The goal of the Geometric Design is to calculate the design parameters for a linkage that allows the end effector to be in contact with an object in its workspace during the motion and satisfies the given task requirements. The task requirements can be position, velocity and acceleration or can also be performance variables like dexterity, cost, robustness etc... This Geometric Design Problem proceeds in four stages:

2.1.1 Task Specification

Task specifications are the end effector locations of contact with velocity and acceleration compatible with the relative curvature of the contacting surfaces. The task includes a set of specifications: positions, velocities and accelerations. Position specification consists of six variables, three for position with reference to the reference frame and three angles signifying longitude, latitude and roll. The velocity task includes three linear velocities in X, Y and Z directions and three angular velocities. The acceleration task is three linear accelerations along coordinate axes and three angular accelerations about the coordinate axes. The velocity and acceleration specifications are derived from the contact and curvature requirements needed for the arm.

2.1.2 Topology Selection

Topology is the kinematic structure of the manipulator without the reference to its dimensions. This is the selection of the serial chain to be designed to achieve the given task specifications or the functional requirements. The serial chain's workspace is the major factor in the decision process. The serial chain's workspace has to contain the given task specifications. Manipulators with different workspaces are used for different applications like Welding, Pick and place, space exploration. Each task may impart different functional demands on the topology of serial chains. There are some techniques which are based on graph theory and expert systems that will aid in topological selection

[4]. In a design problem, synthesis makes best use of the knowledge and the available information to generate a set of feasible practical solutions. These solutions will be matched against the requirements of designer. The one design which meets the requirements closest is possibly the best design. Type synthesis provides us with the way to select appropriate robot mechanism to meet our demands. There are three methods for type synthesis: screw theory based method, displacement subgroup based method and position and orientation characteristics (POC) based method. Rigid body displacement subgroup theory was first introduced into mechanisms by Herve in 1978 [5]. In [6], kinematic chains are classified based on Lie algebraic structure of displacement group. There are totally 12 subgroups and their mechanical bonds can be used to describe relative displacement between any two links of a mechanism. This sub group method of synthesis was not applicable to all the mechanisms but only to those which obey the Lie group. In 1983, Ting Li Yang put forward a method for type synthesis of single loop mechanisms in [7], this method was later developed into POC based method. The screw theory extends the notion of Euler's rotation theorem and says that all rigid body motion can be represented as a rotation about an axis along with translation about the same axis.

The mechanism can be represented by the concepts of constraint and freedom, wrench system represents constraints, whereas the limb of twists represents freedom, then a mechanism is constructed using linear combination of these twists [6] and [8]. Fang, Tsai formed a systematical approach to synthesis of 4DOF, 5DOF constrained parallel mechanisms to both symmetric and asymmetric limb structures [9]. This work was later extended by Huang, Kong and Li in [10], [11] and [12].

2.1.3 Dimensional Synthesis

The goal of the serial chain synthesis is to calculate design parameters for the serial chain (link lengths) and to design a linkage which allows the end effector to be in contact with object in workspace during its motion. There have been two approaches by the researchers in synthesizing the dimensions: Exact synthesis and Approximate synthesis.

Exact synthesis computes the dimensions of serial chains to achieve a specified set of task positions. In [13] Mavroidis and Eric lee expand on the geometric design of a spatial R-R open loop kinematic chain from the paper [14] by Tsai and Roth, where the similar problem is solved using screw theory, they used screw displacements to obtain the design parameters, Mavroidis and Eric solve the problem using DH parameters [15] of the robot arm. The DH parameters were introduced by Denavit and Hartenburg in 1955 [16] can be used for modeling any n DOF robot manipulator [17]. Mavroidis and Lee generate a six-degree polynomial, whose two real roots generate the solution to R-R spatial linkage. The extension of this work was applied for solving the problem of a Spatial 3R Robot manipulators and RPS Serial chains to the design of RRP, RPR and PRR serial chains in [15]. The design follows two approaches: Polynomial solution methods and Algebraic elimination methods. Though Polynomial solution methods were computationally intensive, they can solve equations of high degree, but algebraic elimination is needed for use in a practical system and for on-line computation and solving.

In Approximate synthesis method, solutions are found by finding out local minima corresponding to a performance metric. This method calculates the dimensions of the platform systems to optimize workspace manipulability. Approximate synthesis methods are recent advancements among synthesis techniques. In [18] Saggere and Kota researched on the planar four bar mechanisms when compliant motion is considered. This literature is further expanded by Tokunaga, Matsuki, Imamura, Tanaka and Kishinami, in [19], they solve for the kinematic design of mechanisms in order to reduce constraints using Lie algebra. The advantage of this method is that it can solve for large number of parameters.

2.1.4 Trajectory Planning

The final stage of the geometric design process is to generate a trajectory through the precision points for the end effector of the serial chain. The smoothness of the trajectory forms an important issue. The equation for the trajectory incorporates the changes induced by the velocities and accelerations as given in [20].

2.2 Summary of the Literature Survey

The main motivation for the present research comes from Rimon and Burdick in their papers [21] and [22]. Their research on the 1st order mobility and 2nd order mobility underlines the importance of synthesizing serial chains for grasp applications.

Rimon and Burdick worked on the issue of immobility and introduced the concepts of 1st order mobility and 2nd order mobility indexes. The mobility is based on the free motion of the body grasped by frictionless contacts. The free motion is the local motion of the body when held in contact by stationary fingers. These free motions cannot be prevented by any combinations of the frictionless contacts.

The mobility in a grasp application is measured by the respective indexes. 1st order mobility theories cannot differentiate between equilibrium grasps involving the same number of fingers. The 1st order index classifies the grasps according to the number of contact points involved in the grasp. Thus the 1st order mobility measurement was too crude to conclude the grasp application case. They extended their work to 2nd order mobility. Only the 2nd order index distinguishes between alternative equilibrium grasps involving the same number of fingers. Thus the 2nd order theory provides a finer mobility characterization than is predicted by 1st order theories, such as Screw Theory. Second-order immobility, which relies upon the use of surface curvature effects to reduce the number of fingers needed to immobilize an object, is a remarkable concept developed through their work. Its validity was investigated when practically important effects of compliance are taken into account. Thus by considering 2nd order mobility, the number of grasp points required to constrain an object have been considerably reduced i.e. general theory says that “k+1” grasps are needed to constrain an object in “k” configuration space, for e.g. in planar case, where k=3, we need 4 grasp points and in spatial case where k=6, we need 7 grasp points. With the help of 2nd order mobility it has been shown that when the curvature is taken into account, the object can be stabilized and constrained with 3 grasps in planar and 4 grasps in spatial spaces.

Thus, for designing an end effector to perform a grasp application, the velocity and acceleration requirements are obtained through the 2nd order mobility consideration. By analyzing the curvature and contact specifications of the object at that instant, we get the velocities and accelerations to be maintained at that instant. Once the velocities and accelerations are obtained, then a serial chain is synthesized to meet the task specifications.

3. CONTRIBUTIONS

This research deals with the application of the Failure Recovery Synthesis technique formulated by Dr. Robson and Dr. McCarthy through an experimental set up and synthesis of TS spherical chains for some real world applications:

1. Development of an Experimental Set up for testing of a novel recently developed synthesis technique for joint failure recovery of robot manipulators.
2. Applications of the design of spherical linkages in real world tasks.

4. GEOMETRIC DESIGN OF A TS MECHANICAL LINKAGE WITH DIFFERENTIAL TASK SPECIFICATIONS

Spherical TS mechanical linkage is a serial chain with a T joint joined to S joint. The joints of the robot arm are all revolute. The T joint is a combination of two revolute joints, which are perpendicular to each other and intersect at a point. The S joint is a combination of three revolute joints, which intersect at a point as shown in the Figure 1.

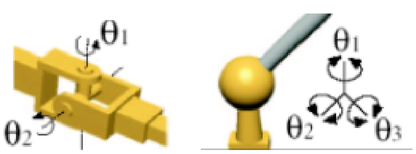

Figure 1. 'T' and the 'S' joints

The distance between the T and S joints is a constant "R". The T joint is responsible for translational degrees of the robotic wrist and the S joint is responsible for orientation of the wrist. The points '**B**' and '**P**' represent the base pivot and moving pivot of the TS robotic arm. The T joint's rotation about the horizontal axis defines the shoulder elevation and its rotation about the vertical axis provides the shoulder azimuth. The S joint's rotation about the three different axes provides Latitude, Longitude and Roll motions for the wrist. To design a TS chain, we need to know the parameter '**B**', '**P**' and the distance 'R'. The TS chain is a spatial spherical chain, which base pivot '**B**' has three parameters: B_x, B_y and B_z, and moving pivot **P** has three parameters: P_x, $P_y$and P_z . We solve for 7 parameters for the TS chain as shown in Figure 2.

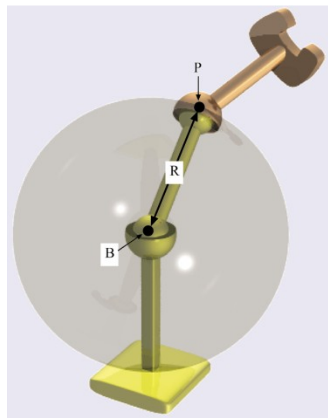

Figure 2. 'TS' serial chain

4.1 Stages of Geometric Design for the TS Chain

There are different stages involved in geometric design as outlined below.

4.1.1 Task Specification

Task specifications are a set of positions, velocities and accelerations. Task specifications specify the end effector locations of contact, velocity and accelerations. These positions are called precision points. If we consider velocity and accelerations in addition to the positions, these become differential task specifications i.e. specifications with velocity and acceleration shown in Figure 3.

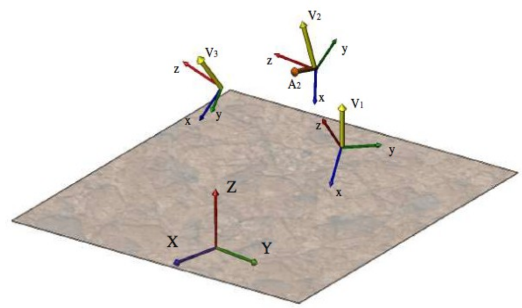

Figure 3. Task specifications of a moving frame M with respect to a fixed frame F

A solution becomes determinate only when number of unknowns equal number of equations. The equations in this case represent equations of Position, Velocity and Acceleration. To solve for the unknowns (three for the fixed pivot **B**, three for the moving pivot **P** and one for the length R), we need 7 equations in terms of position, velocity and accelerations.

We design the TS chain for acceleration specification; this brings four combinations of task specifications given by T_i :

$$T_1 = \{P_1V_1A_1, P_2, P_3, P_4, P_5\}$$

$$T_2 = \{P_1V_1A_1, P_2V_2, P_3, P_4\}$$

$$T_3 = \{P_1V_1A_1, P_2V_2, P_3V_3\}$$

$$T_4 = \ P_1V_1A_1, P_2V_2A_2, P_3 \qquad (4.1)$$

We are designing a TS chain; hence the topology selection is the selection of this TS chain to meet the task specifications.

4.1.2 Synthesis of TS Chain

There are two approaches in the synthesis of serial chains, Approximate synthesis method and Exact synthesis method. We follow the Exact synthesis method. Exact synthesis method's goal is to find the design parameters: link lengths and the coordinates of the base point and the moving point of the wrist of the robot arm, given the task specifications or the requirements of the design.

The TS chain is a spherical mechanical linkage, i.e. the mechanism which can position its end effector in a workspace of a sphere. For the velocities, accelerations and positions to be measured, we need a common reference frame. We get the position variables and the differential specifications: velocities and accelerations, by differentiating position variables with respect to a fixed frame. Kinematic specification is the specification of all the end effector positions, velocities and accelerations with respect to an inertial frame of reference.

4.1.3 Kinematic Specification

If we have planar motions, an object which is to be positioned in a plane can be described by three parameters, its distance from the X-axis and distance from the Y-axis and the orientation with respect to one of the axes as shown in Figure 4.

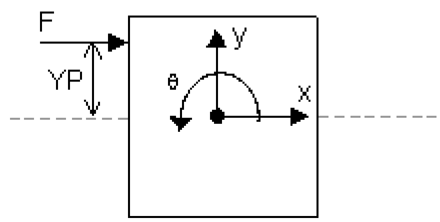

Figure 4. A planar body

Similarly an object in 3D space with its spatial movement is defined by three orientation coordinates: (θ, φ, ψ) representing Longitude, Latitude and Roll about the X, Y and Z axes respectively and the body's translational coordinates: **d** = (d_x, d_y, d_z) along the three axes respectively. All the six coordinates are represented in moving frame of the body M with respect to a fixed frame of the body F.

Let the movement of a rigid body be defined by the parameterized set of 4 X 4 homogeneous transforms [T(t)] = [R(t); d(t)] constructed from a rotation matrix, A(t), and translation vector d(t). The transformation of coordinates of both position and orientation from the moving frame M to a fixed frame F can be represented through this 4*4 Matrix called Homogeneous Transformation Matrix given by:

$$[T(t)] = \begin{matrix} c\text{Ø}c\varphi\text{-}s\theta s\text{Ø}s\varphi & \text{-}c\varphi s\text{Ø}s\theta\text{-}c\text{Ø}s\varphi & c\theta s\text{Ø} & d_{x,i} \\ c\varphi s\theta & c\theta c\varphi & s\theta & d_{y,i} \\ c\varphi s\text{Ø}\text{-}c\text{Ø}s\theta s\varphi & \text{-}c\text{Ø}c\varphi s\theta + s\text{Ø}s\varphi & c\varphi c\theta & d_{z,i} \\ 0 & 0 & 0 & 1 \end{matrix} \quad (4.2)$$

The movement of the frame M relative to the fixed frame F in the vicinity of the reference position defined by t=0 is given by the Taylor series expansion given by equation.

$$[T(t)] = [T_0] + T_1 t + \frac{1}{2} T_2 t^2 + \cdots., where\ T_i = \frac{d^i}{dt^i} T \quad (4.3)$$

The Taylor series corresponding to a function $f(x)$ at a point x_0 is the infinite series whose nth term is $(1/n!)\cdot f^{(n)}(x_0)(x - x_0)^n$, where $f^{(n)}(x)$ denotes the nth derivative of $f(x)$. Where [T (0)] = $[T_0]$ is the reference position of the end effector. The matrices T_0 , T_1 and $[T_3]$ in the Taylor series expansion are defined by the position, velocity and acceleration task requirements.

A point p fixed in the moving body traces a trajectory P(t) in the fixed frame The points Pi in the moving frame can be represented by the relative transformation matrix, by which any point Pi can be represented with respect to one of the points in the moving frame.

We introduce a relative transformation D(t): $D\ t = T\ t\ [T_0]^{-1}$, which operates on point coordinates measured in the fixed frame. Point p in M, has a trajectory P (t) in the fixed frame F given by Figure 5.

$$P\ t = [T_0] + T_1\ t + \frac{1}{2}\ T_2\ t^2 \ldots.]p \quad (4.4)$$

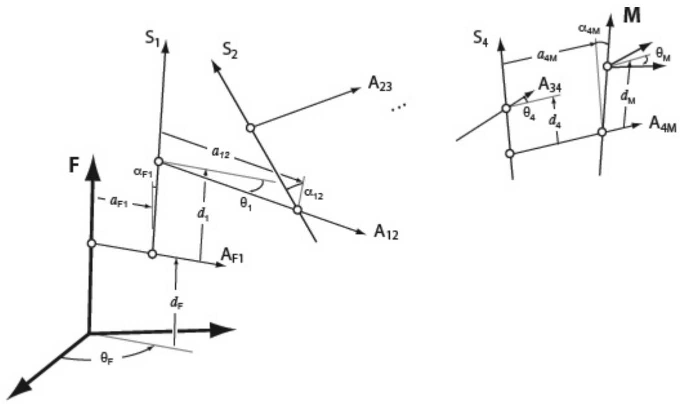

Figure 5. Description of a moving frame M and a fixed frame F

This makes us convenient to substitute P= $[T_0]^{-1}p$

to give $P \ t \ = [[T_0] + \ T_1 \ t + \frac{1}{2} \ T_2 \ t^2 \ \ldots.][T_0]^{-1}p,$

$$= \ I + \ \Omega t + \frac{1}{2}\Lambda t^2 + \cdots. \ \ p = [D(t)]p \qquad (4.5)$$

The equation 4.5 shows that when the velocities and accelerations requirements are given by the designer, the dimensions of the serial chain can be synthesized.

4.2 Design Procedure

The design procedure starts by considering one of the 4 task specifications as needed by the designer.

The set of positions reached by this manipulator can be expressed as the positions lying on this sphere generated by the end effector and can be mathematically expressed as:

$$P\;t\;-\boldsymbol{B}\;.\;P\;t\;-\boldsymbol{B}\;=\;R^2 \qquad (4.6)$$

where the P(t) represents the trajectory of the points in the moving frame M and **B** represents the base point with respect to the fixed frame F. R represents the constant distance between the two points **B** and **P** as given in the Figure 2.

By differentiating the position equation, we obtain the velocity and acceleration equations as:

$$\frac{d}{dt}\boldsymbol{P}.\;\;\boldsymbol{P}-\boldsymbol{B}\;\;=0 \qquad (4.7)$$

$$\frac{d^2}{dt^2}\boldsymbol{P}.\;\;\boldsymbol{P}-\boldsymbol{B}\;+\;\frac{d}{dt}\boldsymbol{P}\;\;.\;\;\frac{d}{dt}.\boldsymbol{P}\;\;=0 \qquad (4.8)$$

From the relative transformation matrix, we obtain

$$P^i=\;D_{1i}\;\boldsymbol{P}^1 \qquad (4.9)$$

The position, velocity and acceleration derived from this equation are:

$$D_{1i}\;\boldsymbol{P}^1-\boldsymbol{B}\;.\;\;D_{1i}\;\boldsymbol{P}^1-\boldsymbol{B}\;\;=\;R^2, i=1{,}2\ldots n. \qquad (4.10)$$

$$W_i\;D_{1i}\boldsymbol{P}^1\;\;.\;\;D_{1i}\boldsymbol{P}^1-\boldsymbol{B}\;\;=0, i=1{,}2\ldots n \qquad (4.11)$$

$$W_i \quad D_{1i}\, \boldsymbol{P}^1 \;.\; D_{1i}\, \boldsymbol{P}^1 - \boldsymbol{B} \;+\; W_i \quad D_{1i}\, \boldsymbol{P}^1 \;.\; W_i \quad D_{1i}\, \boldsymbol{P}^1 \quad = 0, i = 1,2..n$$

(4.12)

where

$$\frac{d}{dt} P^i = [W_i][P^i] \tag{4.13}$$

and

$$\frac{d^2}{dt^2} P^i = [\Lambda_i][P^i] \tag{4.14}$$

Wi, Λi are obtained from the original Taylor series expansion as

$$W_i = T_1 \, [{T_0}^{-1}] \tag{4.15}$$

and Λi is given by

$$\Lambda_i = T_2 \, [{T_0}^{-1}] \tag{4.16}$$

These equations help us to solve for the seven parameters B_x , B_y and B_z, and P_x, P_y and P_z and the distance R. Thus a serial chain is obtained with the seven parameters which can satisfy all the task requirements of position, velocity and acceleration.

Once the serial chain is designed, the smooth trajectory of the chain needs to be ensured as it passes through the given task. To solve this problem, trajectory planning has been done.

4.3 Trajectory Planning

Trajectory refers to the time history of position, velocity and acceleration for each degree of freedom. In order to make the description of manipulator motion easy for the end user of the robot system, the user should not be required to write down complicated functions of space and time to specify the task. Rather, we must provide him with the ease of specifying trajectories with the descriptions of desired motion and the system figure out the details i.e. if the user specifies the desired goal position and orientation, the system figures out the details like the exact shape of the path to get there, the acceleration and velocity profiles and so on then the trajectory is generated.

Generation of the trajectory must occur in run time, and the rate at which trajectory is computed is called the Path Update Rate. In typical manipulation systems, this is around 20 to 200 Hz.

As the manipulator designed must go through the required start and end positions, with some via positions and additionally, must satisfy the requirements of velocity and acceleration, the path is specified mathematically by a higher order polynomial system.

Figure 6. Trajectory with two via points

Task example is introduced in the Figure 6. If we have four different positions for the end effector to reach and incase it possesses predefined velocity in two of the positions, and acceleration in one of the position, then first, the trajectory can be analyzed from the point1 to via point1, then via point1 to via point2 and finally from via point 2 to point 2.

In each of the points, the position, velocity and acceleration are taken. In between a start and an end point, we have six parameters: Initial position, Final position, Initial velocity, Final velocity, Initial acceleration, Final acceleration as given in the Table 1.

Table 1. The initial and final positions, velocities and accelerations

Index	Position (rad)	Velocity (rad/s)	Acceleration (rad/s^2)
Initial	θ_0	θ_0	θ_0
Final	θ_f	θ_f	θ_f

Thus we consider a five degree polynomial to generate a trajectory in our case:

$$\theta\ t\ = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5, \qquad (4.17)$$

where a_0, a_1, a_2, a_3, a_4 and a_5 are six constants to be solved for between any two precision points

$$a_0 = \theta_0,\ a_1 = \theta_0,\ a_2 = \frac{\theta_0}{2},$$

$$a_3 = \frac{20\theta_f - 20\theta_0 - \ 8\theta_f + 12\theta_0 \ t_f - (3\theta_0 - \theta_f)t_f^2}{2t_f^3}$$

$$a_4 = \frac{30\theta_0 - 30\theta_f - \ 14\theta_f + 16\theta_0 \ t_f - (3\theta_0 - 2\theta_f)t_f^2}{2t_f^4}$$

$$a_5 = \frac{12\theta_f - 12\theta_0 - \ 6\theta_f + 6\theta_0 \ t_f - (\theta_0 - \theta_f)t_f^2}{2t_f^5} \qquad (4.18)$$

The angular velocities, angular accelerations are obtained from the respective Jacobians J_i:

$$V_i = \ J_i \ q_\iota, i = 1,2, \qquad (4.19)$$

$$A_i = \ J_\iota \ q_\iota + \ J_i \ q_\iota, \ i = 1 \qquad (4.20)$$

$$where \ q_{\iota\iota} = [J_i^T J_i]^{-1} \ J_i^T \ V_i, i = 1,2. \qquad (4.21)$$

$$and \, q_\iota = \ J_i^T J_i \ ^{-1} \ J_i^T \quad A_i - J_\iota q_\iota \qquad (4.22)$$

We consider the pseudo Jacobians here, as we have to eliminate the singularities or the null points which cannot be reached by the manipulator [23]. The solution to this TS chain can be obtained by Algebraic elimination method given in [24].

The Task with the positions, velocities and accelerations is defined as in Table 2.

Table 2. The task specification for the synthesis of TS chain

Position	{θ,φ,ψ,d_x, d_y, d_z}[m]	Velocity[m/s]	Acceleration(m/s^2)
1	{0,π,-$\frac{\pi}{2}$, 0,0, −0.35}	{0,0.1,0.3,0.03,0.1,0}	………………..
2	{0,0,− $\frac{\pi}{2}$, 0,-1,-0.8}	{0.1,0,0,0.02,.03,.12}	{0,0.1,0,-0.3,.1,0.1}
3	{0, π,- $\frac{\pi}{2}$, 0,0.5,0.7}	{0,.1,.1,.1,0.02,.03}	………………......

The parameters **B** and **P** are calculated by the code to synthesize TS chain with the following parameters as in Table.3. Figure 7. shows the synthesized TS chain.

Table 3. Solution to the synthesis of TS chain

B [m]	**P [m]**	R [m]
{-3.84,-.80,-0.05}	{-4.87,-0.75,-0.72}	1.2293

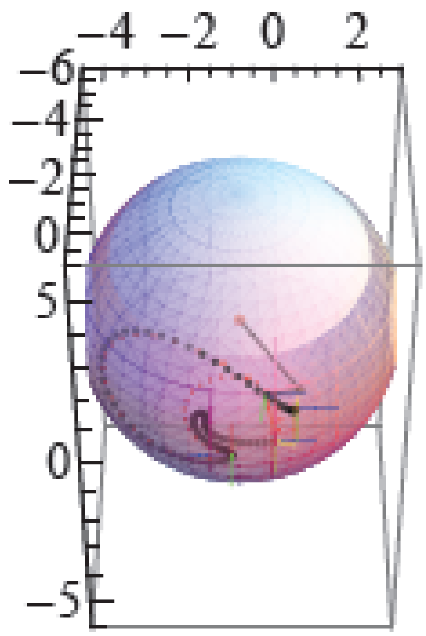

Figure 7. TS chain synthesized in Mathematica

5. EXPERIMENTAL VALIDATION OF THE EXISTING FAILURE RECOVERY SYNTHESIS TECHNIQUE

5.1 Failure Recovery Synthesis Technique

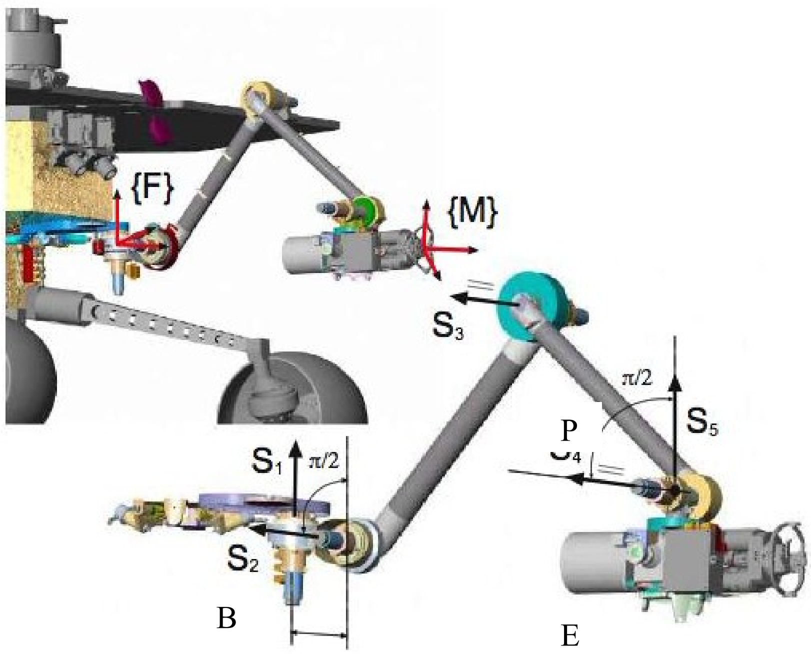

Figure 8. The robot arm mounted in front of the Mars Rover

The recovery plan is achieved by determining the reconfiguration parameters **B**= (B_x, B_y, B_z), and **P**= (P_x, P_y, P_z) in Figure 8. This assures that the end-effector can achieve the specified task for each failure of the actuator. Re-grasping ability of the end-effector is assumed. If one of the joints of the robot fails, we fix it at a particular angle and then we reposition the base of the platform in such a way that the arm is able to complete the task irrespective of the failure. The task is specified as in Figure 3. The velocity and acceleration specifications are important for the end effector to satisfy at that particular point, because the velocity is compatible with contact and acceleration with curvature requirements of the object to be tested.

To experimentally validate the existing failure recovery technique, a system of robot arm and platform is built. The positions, velocities and accelerations to be possessed by the end effector of this arm are derived from contact and curvature of the end effector with its environment. The experimental set up to validate the failure recovery technique was developed with regard to the NASA Mars Rover. The failure recovery technique finds the new location for both the fixed and moving point on the robotic arm, and the grasp point at the end effector to achieve the originally specified task despite the failure in one of the robotic joints.

In what follows, the thesis shows how a novel synthesis technique for failure recovery for a rover subject to joint failures can be experimentally validated by means of a robotic arm and a mobile platform.

The platform and arm unit was chosen as per the adaptability to challenging environments. The platform is sturdy enough to go through the rough and irregular surfaces and the arm has 5 degrees of freedom to emulate the failure recovery technique.

5.2 Problem under Consideration: Elbow Joint Failure

The arm we put together in our laboratory is a TRT configuration (see Figure 9),

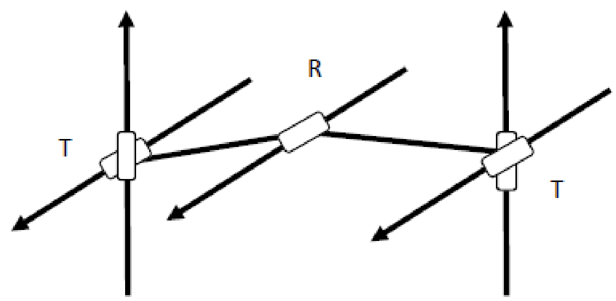

Figure 9. The 'TRT' serial chain

where T stands for a combination of two rotary joints and R stands for a rotary joint as shown in the Figure 10. The arm was chosen, since it has a kinematic structure similar to that mounted on the Mars Rover.

Figure 10. The 'R' revolute joint and the 'T' joint or the universal joint

In the TRT manipulator, when a failure in elbow joint of the arm is considered, the arm results in a serial four degree of freedom TT kinematic chain. The workspace of this T-T chain is equal to that of a T-S chain and is a sphere.

The crippled arm was simulated using Mathematica. The length between the T joint at base and T joint at wrist is a constant and equals to R. The solution to this file gives the new reposition parameters of point **B** (Fixed Pivot), point **P** (Moving Pivot) and a new grasp point for the tool or work piece.

5.2.1 The Movable Platform

The Surface Mobility Platform from Gears Ed Inc. was chosen as a moving platform for the system and shown in the Figure 11. It is made from Aluminum alloy, operated by the DC motors that replicate the Tank mechanism.

Advantages of This Platform

Surface Mobility Platform has an ability to be All-Terrain vehicle. It can go on rugged surface just like the platform of Mars Rover. This ability has been made possible by an innovative suspension system incorporated at the rear of the vehicle. The suspension system with the Tie Rods makes the platform pivot across the central shaft. This makes the robot to go across irregular surfaces. The shaft is made of Titanium alloy, just to be suitable for robust applications. The chassis, wheels, motors and other parts like shaft, nuts and bolts were provided by Gears Education System Inc. DC Motors run on 12V DC power supply and have a gear ratio of 65.5:1, each motor can take 8lbs of force and a standing current of 2.25 Amps for each wheel. The 12V DC voltage goes into Electronic Speed Controllers. The use of ESC's is mentioned in the

ESC Section- Appendix. A. This ESC's drive the motors with the appropriate voltages and logic. ESCs are very useful in debugging and testing the functionality of motors. Lately in the project, we realized that we may need a feedback mechanism to be incorporated in the platform to get the distances traversed by wheels, for this purpose, we integrated four encoders to each of the motors.

The platform was integrated and casing was designed for the Battery, Real-time board, Controller of arm and other electronic parts to reside.

Figure 11. The SMP platform

5.2.2 The Robot Arm

The Robotic arm is from Lynxmotion Inc. (AL5D) and is shown in the Figure 12. It is five degrees of freedom arm. The movement in five degrees made possible by the servos in the arm at five joints of the robot. Geometrically, this arm is of T-R-T configuration. The first two joints (T) are responsible for movement of shoulder: Shoulder elevation, Shoulder Azimuth. The R joint resembles Elbow in human arm, responsible for flexion and extension. The final two joints again form a T- joint which represents wrist of the Robot manipulator: Pitch and Roll angles. In addition, we have a movement of closing and opening of the gripper. This robot arm works on 9V battery supply and the control signals to control the servos of the robot can be supplied through a controller, SSC 32. This is a serial controller connected to the Master controller through RS 232.

Figure 12. The robot arm

5.2.3 Integration of the Robot Arm and Platform System

Figure 13 shows the integration of the robot arm with platform along with a controller for the failure recovery logic to be demonstrated. The Master Controller can work with both Arm and Platform once the process has been initiated. The Master Controller is the NI sbRIO 9632XT (The Single Board RIO Model#: 9632). The specifications of the controller are given in the NI sbRIO Section in Appendix B. This controller works on 24V Power Supply. A Lithium Metal Hydride battery is used from Tenergy Inc. which supplies 12V DC to power various units. A voltage regulator converts this 12V DC to 24V DC to power up the Master controller.

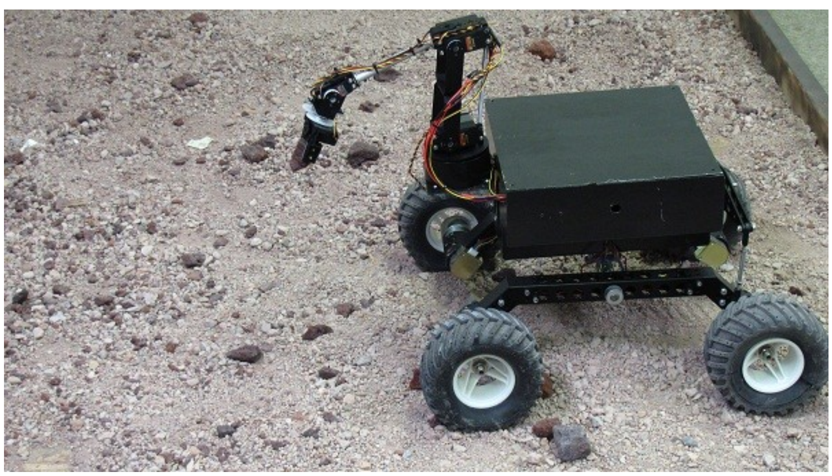

Figure 13. Integration of the Lynxmotion AL5D robot arm on the SMP platform

5.3 Components in the Casing

As discussed earlier a casing was manufactured to hold the components which control Robot arm and Platform in a closed and protective environment, it serves an additional purpose of holding Robot arm from base to the end effecter. The platform could hold about 30 pounds of weight which made us realize the possibility of including a casing and integrating arm on the casing. The casing has some parts of the Control System, Power System Communication system and the Robot arm as shown in Figure 14.

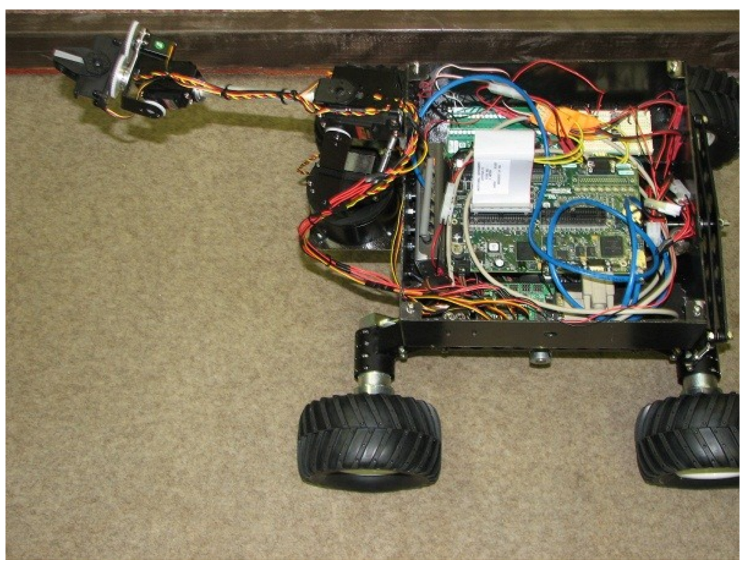

Figure 14. Casing of the SMP platform

5.4 Control System

When in open loop control, we aim to control the platform and arm simultaneously i.e. a simultaneous multi-axis control in arm is desired. Therefore, a control architecture was designed. It is divided into three stages; the first stage is the Computer or the Laptop stage which sends the commands necessary for controlling the platform with a certain speed and acceleration. (See Figure 15.)

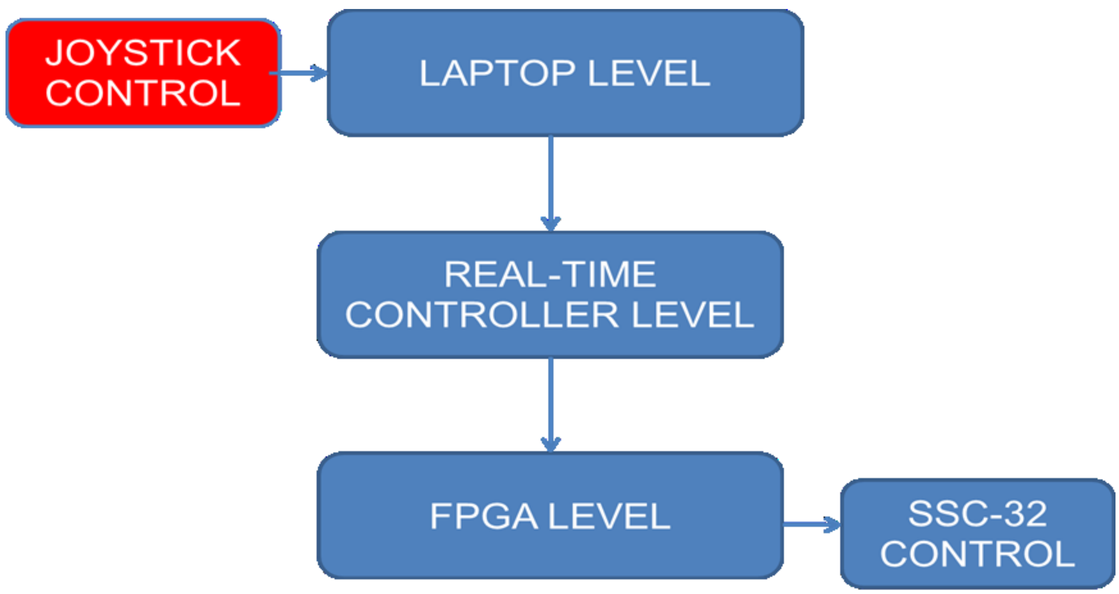

Figure 15. Architecture for the control of arm and platform

A Logitech Joystick is used for the simultaneous control of different axes in a robotic arm. It has 11 axes control for simultaneous control. We use 8 buttons out of these 11 buttons to control the movement of arm. Out of these 8, 6 buttons are used to control a specified direction of the axes or each of the joints- All 5 + the robot's gripper.

The remaining 2 buttons control a special motion which includes Home Position and Ready Position.

Home Position

This is the original resting position of the arm, when the arm is no longer in operation or when the arm is yet to be operated. (Default when arm not activated)

Ready Position

This is the first working position of the robot, from this position; the robot's movement can be controlled in different axes by the use of the Joystick. (Default when arm gets activated)

Computer Arrow Keys on Keyboard

This part of the computer is used to control the Platform movement. UP arrow signifies FORWARD movement. DOWN arrow signifies BACKWARD movement. The remaining LEFT and RIGHT correspond to turning in the respective directions of the platform.

The system is programmed in such a way that the robot is in stowed position when the platform is in motion, once the platform executes its motion, that is once it comes closer to the target, where arm has to be activated to complete the task , then the arm is released and the necessary operation is undertook.

- Front Level Control: This control is the input control by the user, it takes in several values like the Booleans for the directions of the movement of arm and the platform, speed and acceleration values of the platform, period for the timing loop of the program, Start and Stop controls for different stages of the architecture. The front panel and the block diagram controls are made possible using LabVIEW 2010, a great user friendly tool, with which numerous custom hardware applications can be initiated, controlled and automated.
- Mid Level Control: This program is used to pass the variables of the user to the Real-Time controller, also initializes Field Programmable Gate Array to make it to receive the data from the user.
- Low Level Control: This control is precisely the Field Programmable Gate Array Control in the control of motion of the platform. The FPGA then sends and receives appropriate signals from the pins.

The programs in LabVIEW are called VIs (Virtual Instruments). There are three VIs to control the platform. These VIs reside according to their architecture. The first VI is of top level control, the second VI represents sharing or transformation of information from Computer's keyboard to the Real-Time controller NI sbRIO. The third VI is the FPGA VI; this VI is used to load the FPGA with the necessary values passed by the user. The FPGA port is used to receive the signals from the Encoders, which is transported from the LOW LEVEL to MID LEVEL by shared variables and then to TOP LEVEL for the purpose of feedback.

5.4.1. Programming the Robot Arm

The TOP LEVEL of execution is Computer reading the Joystick values. Since the Joystick conveys the information about the variations in the axes of the robot, the PWM values corresponding to the movements of axes are taken by this VI.

Low level control in this project is the Robot arm controller, SSC 32. The controller is serially connected to the Real- Time controller NI sbRIO 9632XT with RS232. The SSC 32 control sends the appropriate signals to the servos of the robot arm.

SHARED VARIABLES: Whenever we talk of transferring data, the shared variables come into play. Shared variables are solely for the purpose of transferring data from one level of architecture to the next level. The transfer may be executed in different protocols like Ethernet, WLAN, etc.

5.4.1 Software Programming and Execution

Software program is written in LabVIEW and has three architectures, the first is of the computer level, the second stage is of the real-time controller level and the third stage is of the FPGA Level.

LabVIEW programs (VIs) have two separate parts, the front panel and the block diagram. Front Panel is composed of controls and indicators like those on the front panel of a real scientific instrument. The Block Diagram is the context where the algorithm is actually implemented. The Block Diagram is not simply text, like the source files of conventional programming languages. Rather, the diagram graphically represents the flow of data to and from various terminals (diagram representation of the front panel controls and indicators), and external data sources. Data migrates from inputs to outputs along a network of lines, or “wires”. Structural programming or text based programming can also be executed through a program node incorporated in the block diagram.

Code for the Platform: Laptop Level Program

This program accepts commands from the user, the block diagram (Figure 16.) and the front panel (Figure 17.) of the program are represented below, the front panel shows the screen where the user can adjust different parameters, Block diagram depicts the logic involved. The program essentially waits for an event execution at the keyboard, if the user presses the UP key, the forward command is accepted in the switch-case statement, then the appropriate values of the PWM signals are sent to the Left and Right motors. If the user presses the DOWN key, the back command is executed in the Switch-Case, then the values of 45000 units of PWM updates to both the left and right motors. Similarly the cases of LEFT and RIGHT can also be demonstrated.

The default statement is executed in the switch-case statement when the user presses any other key; this passes the value 60000 units of PWM to both the RIGHT and LEFT motors. 60000 PWM units equal the neutral point for the system and the platform does not move. The values of Period, Acceleration can be changed dynamically through the slide and dial by the user as shown in Figure 17.

The components PERIOD1, ACCEL1, PWMRIGHT, PWMLEFT and Greenenc1, yellowenc1, redenc1 shown in Figure 16 are the shared variables.

Program for Real-Time Controller

This program initializes the FPGA VI and checks whether it's compiled or not before execution. This program serves as a mediator transferring the values of the shared variables from TOP Level to FPGA Level or Vice-Versa in case of feedback as shown in Figure 18.

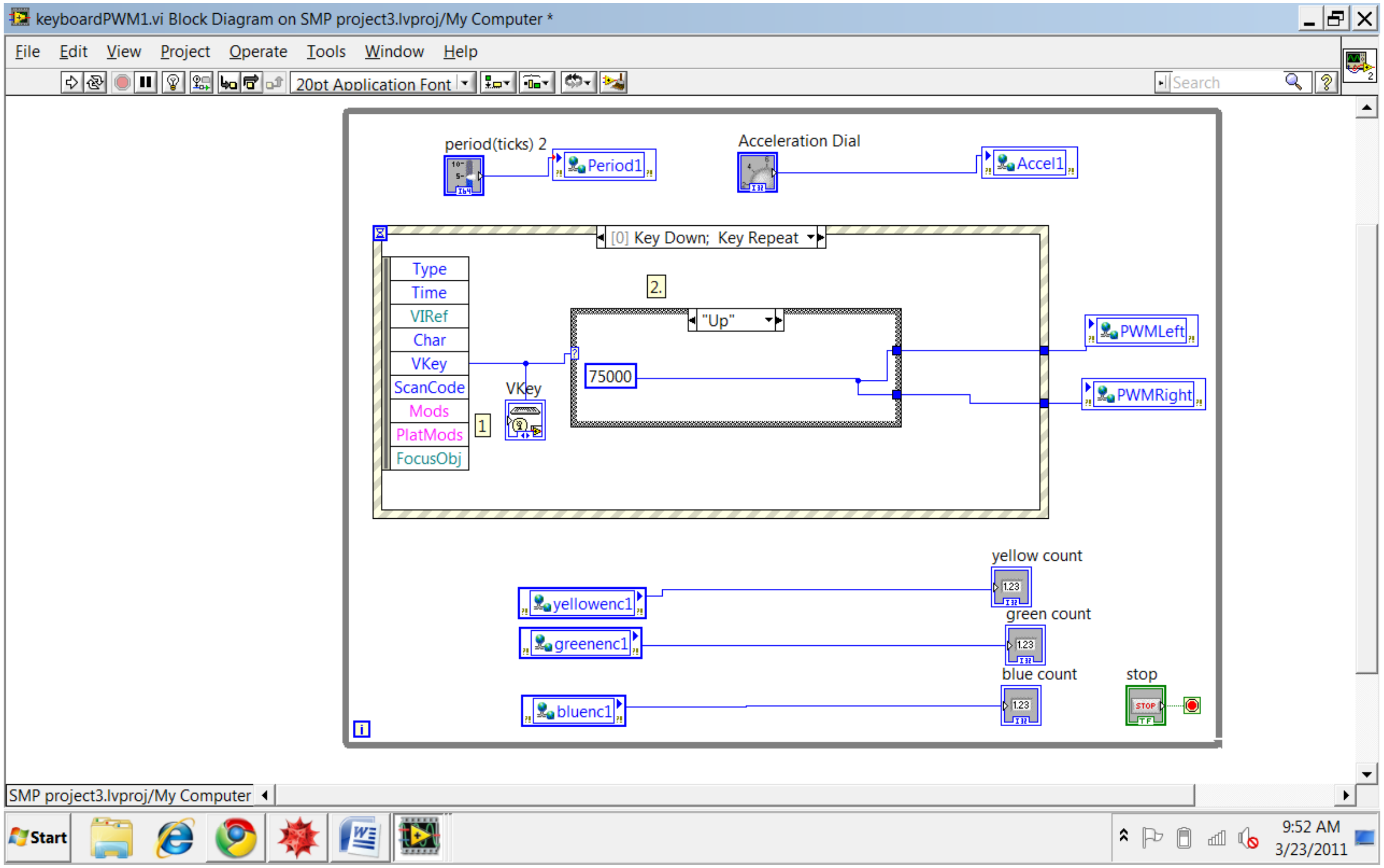

Figure 16. Block diagram interface of LabVIEW VI for top level implementation

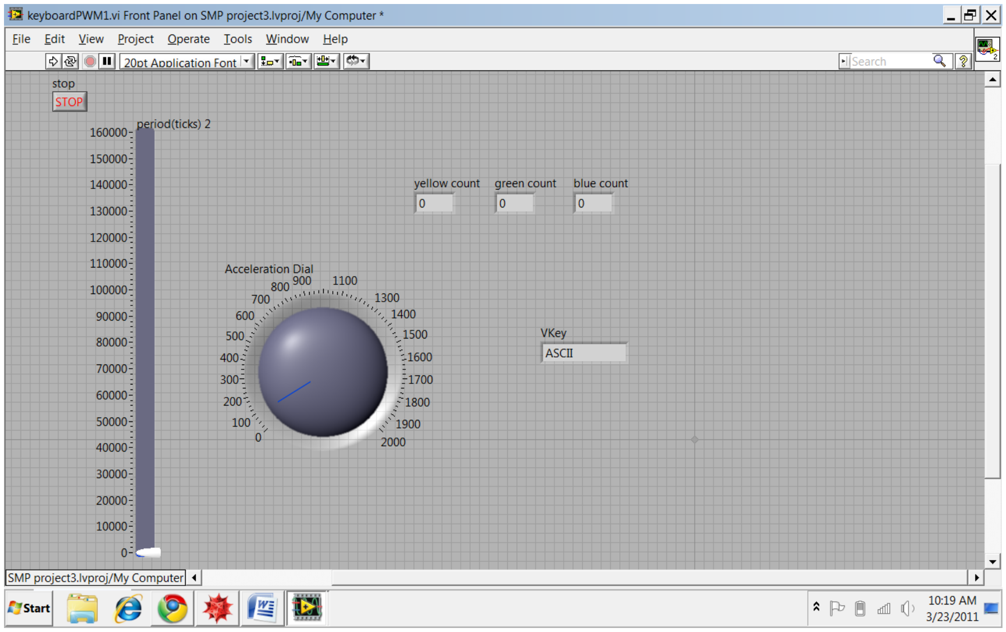

Figure 17. The front panel interface in LabVIEW for top level implementation

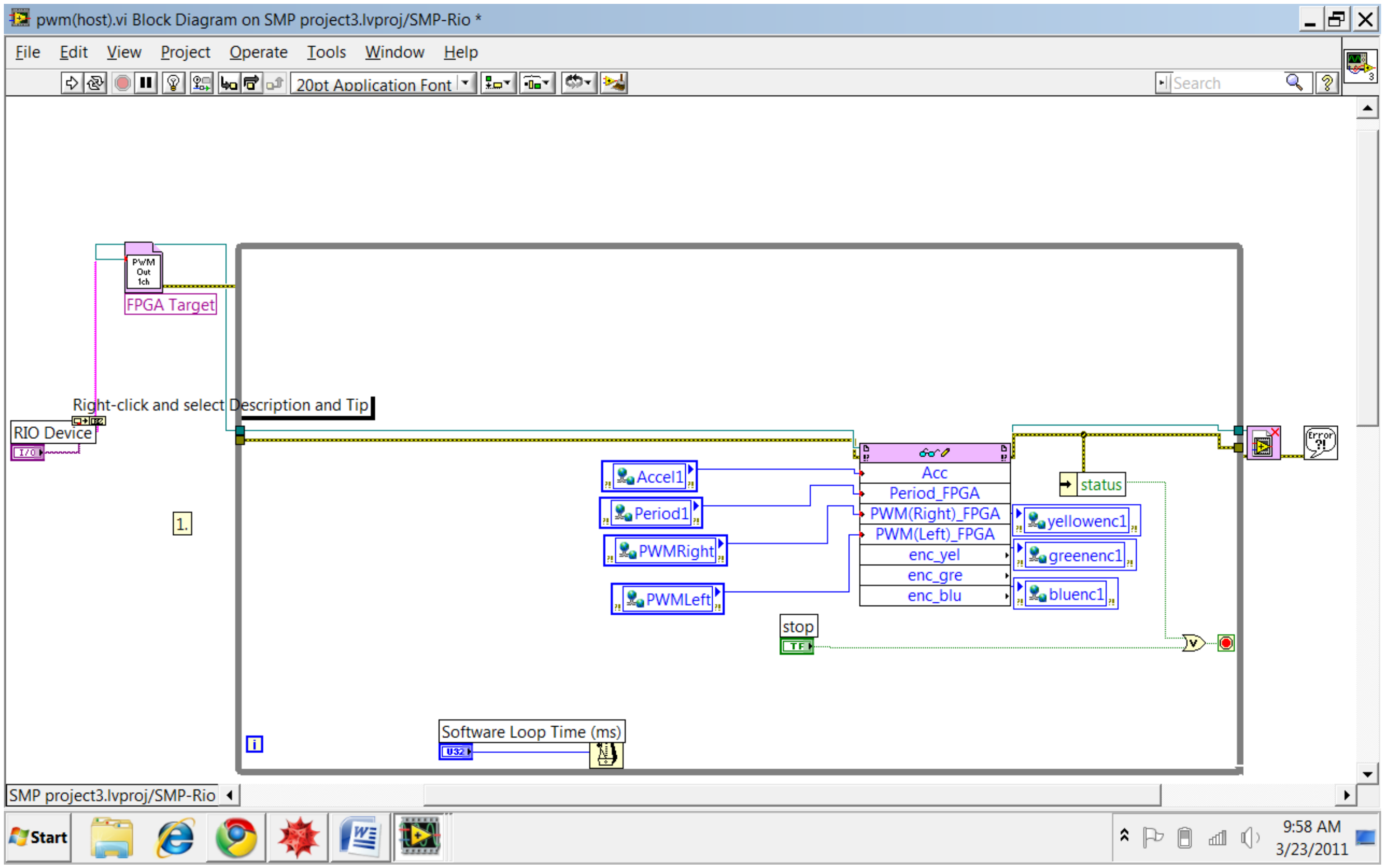

Figure 18. Block diagram in LabVIEW for middle level implementation

Code for the Platform: FPGA Level

This program transfers the signals acquired from REAL-TIME Level to pins on the controller board. This program also collects the values read by the encoder from the pins on the controller board. The program's loop time is determined by the user's PERIOD variable and how fast can it increment signal at pin, or how fast can the FPGA update the pin depends on the value of ACCELERATION passed by the user. The program executes in a sequential way from Left to Right, the first node passes the values of PWM RIGHT and PWM LEFT to the next node, where it goes to the Pin at MOD A, and then in the next sequence, the wait function is executed to hold that value on the pin. The next sequence which forms the end of the program, releases the value at the pin to restore it to the default.

Code for the Robot Arm

This VI senses that Joystick is connected to computer and starts acquiring data from the joystick. Once the data acquiring process is initiated, the PWM values from the joystick are read and checked whether they lie within the limits.

The joint limits of the robot arm have been determined by the Motion Capture System at our Human Interactive Laboratory. VICON motion capture system uses infrared cameras to detect the movement of different joints in the robot arm. The joint limits are specified as in table on page 46. If the PWM values lie within these joint limits, then a switch-case statement executes and it makes sure that the appropriate LED is lit on the front panel with the value shown. The LED interface in the front panel is a way to simplify the debugging and testing of this program. As shown in the Figure 19., the front panel has a set of LEDs in the button info dialog box. These LEDs lit when the exact button is pressed on the joystick. The axis dialog box shows the amount of orientation specified by the user in that direction. The program then downloads itself on to the sbRIO through a local Ethernet connection. From the Master Controller (NI sbRIO 9632XT), the program is sent to the SSC-32 Controller (Controller of Lynxmotion Robot AL5D) through a serial RS232 port. The SSC 32 transfers the PWM value to the appropriate joint.

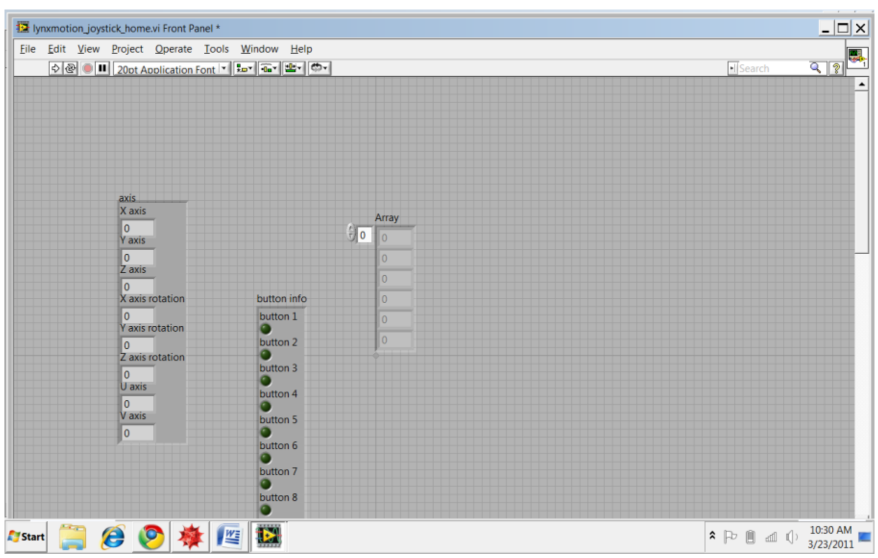

Figure 19. Front panel interface in LabVIEW for robot arm

5.5 Power System

The units that consume power are: DC Motors of the SMP, Router for the communication, NI sbRIO 9632XT, SSC-32 Controller and Robot arm

DC motors run on 12V DC, this power is supplied to the motors through the ESCs. Information about ESCs is given in the Appendix A.

The router uses WLAN connection, requires a power of 5V DC and can take up to 1A. The servos of the robot arm take up a maximum of 6V DC. The 9V battery is used to power up robot arm. The regulation from 9V DC to 5V DC is made possible through a regulatory circuit.

NI sbRIO 9632XT works on a power supply of 24V DC, a regulator converts from 12V DC to 24V DC to power up the controller. SSC-32 Controller operates on a voltage of 9V DC which is supplied directly from a 9V Battery.

5.6 Communication System

The communication between the wireless units is through WLAN protocol, made possible by a router incorporated in the casing of the platform. The laptop which forms the Top Level in the architecture is connected to the router through the LAN connection.

5.7 Testing the Failure Recovery Technique

To test the failure recovery technique, one of the cases of failure of robot joint: Elbow failure has been considered. Mathematica is used at the Laptop level to solve for the failure model, this transports the reposition parameters into LabVIEW. The LabVIEW then computes the PWM values for the motors to move to the new positions and the VIs are executed. The arm had the following task specifications (see Table 4):

Table 4. Task specification for the rover and arm to satisfy

{θ,φ,ψ,d_x, d_y, d_z} [m]	Velocity [m/s]	Acceleration [m/s^2]
{-0.17,0.89,2.48,25.3,3.56,15.2}	{-0.03,0.12,0.16,3.8,0.65,2.7}	
{-0.59,0.55,3.73,12.53,11.3,5.6}	{0.39,-0.5,0.31,-8.6,-8.13,-5.7}	{-0.4,0.5,0.55,0.3,0.3,2.36}
{0.14,-0.4,0.85,18.1,5.63,10.2}		

Initially, the point **B** and the point **P** are calculated using Mathematica. Multiple solutions can be obtained and the choice of the best solution depends on the most practical one. The PWM values corresponding to the movement of platform and the robot arm to reach the task are determined. The PWM values are checked for the robotic arm, to see whether they lie within the specifications or the joint limits of the arm. If the PWM values or the voltages to the servo motors lie outside the joint limits, they are discarded. The joint limits of the robot arm are calculated using VICON motion capture system.

VICON motion capture system captures the movement of different joints of robot arm with the help of infrared markers fixed at strategic locations on the joints of the arm as shown in Figure 20.

Figure 20. Robot arm with infrared markers fixed at different joints

The motion capture system is assembled by three cameras, which note the motion of the joints, hence monitor its displacement, velocity and acceleration with respect to a fixed frame. The cameras are set up as in Figure 21. so that the robot arm is placed within the capture workspace of all the cameras.

Figure 21. Set up of infrared detection cameras in VICON motion capture system

The joint limits of the robot arm are given in Table 5.

Table 5. Joint limits of the T-R-T robot arm

Joint Index	Joint Minimum	Joint Maximum
θ_1	-126.9^0	81.4^0
θ_2	-18.8^0	177.4^0
θ_3	-193^0	13^0
θ_4	-20^0	180^0
θ_5	-90^0	90^0

When the PWM values are within the joint limits of the robot, arm receives the signals from the controller. The platform reaches near the target, when arm remains unreleased or stowed, when the platform approaches the target close enough, then the arm is released and the task is performed.

Elbow Actuator/Joint Failure

With the elbow failure, the resulting chain now becomes a T-T chain as shown in Figure 22. The angle of elbow is fixed at an angle where it fails. In case of our testing, we simulated the failure of the elbow joint of the robot arm by fixing it at an angle of 57.23^0

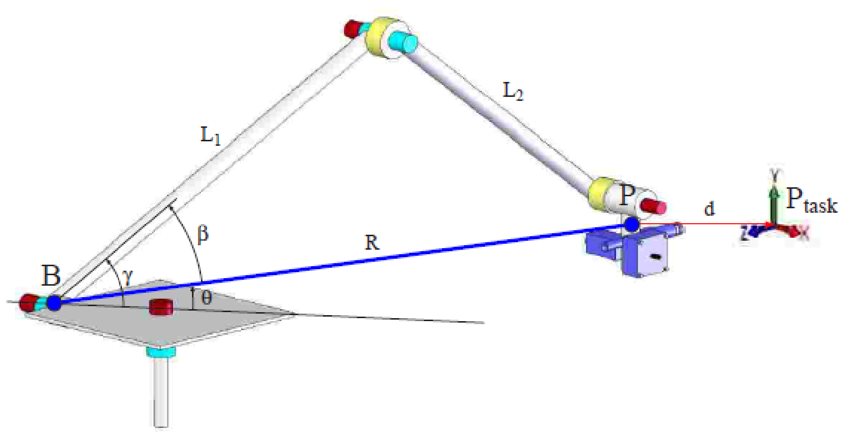

Figure 22. Elbow failure in a T-R-T chain

The fixing of the elbow joint at that angle, introduces a constraint in the robot arm, which is a constant distance between the base pivot and the moving pivot through the equation:

$$R^2 = r_1^2 + r_2^2 - 2r_1r_2Cos(\theta_E) \qquad (5.1)$$

where 'R' is the distance between the shoulder and the wrist of the T-T chain, $r_1$is the distance between the shoulder and the elbow and r_2 is the distance between the elbow and the wrist. θ_E is the included angle between the two links. Therefore, once θ_E is fixed at57.23^0, a constant R can be obtained through the Cosine Law [25].

In case the robot arm loses one of the degrees of freedom i.e. rotation of the elbow, new parameters for the point **B** and the point **P** at the end effector are obtained in order for the arm to reach the originally specified task.

The reposition parameters for the points **B**, **P** and the distance R are calculated from the failure recovery code in Mathematica using the procedure mentioned in the previous section. The new reposition parameters r_p are calculated as $r_p = \{b_x, b_y, p_x, p_y, p_z\}$. As each of the 5 equations are quadratic for the T-T chain, the polynomial solution for this system of equations has 2^5 solutions or 32 solutions. The solutions whose values lie within the joint limits are chosen, this case has obtained two real values which lie favorably within the joint limits as shown in Table 6. where the T-R-T serial chain was able to execute the task despite of the failure in its elbow joint.

Table 6. The reposition parameters in case of an elbow failure

Index	$b_x(cm), b_y(cm)$	$p_x(cm), p_y(cm), p_z(cm)$	R(cm)	$\theta_E(cm)$
1	34.034, 12.342	53.453, 2.354, 3.047	16.73	57.3
2	13.426, 16.541	34.231, 8.574, 1.234	14.32	54.6

The robot arm satisfies the given task even with the healthy arm and also with the crippled arm when the breaks are applied at the failed angle. This failure angle is sensed by a sensor in practical system. The healthy and crippled configurations of the arm are shown in the Figures 23 and 24.

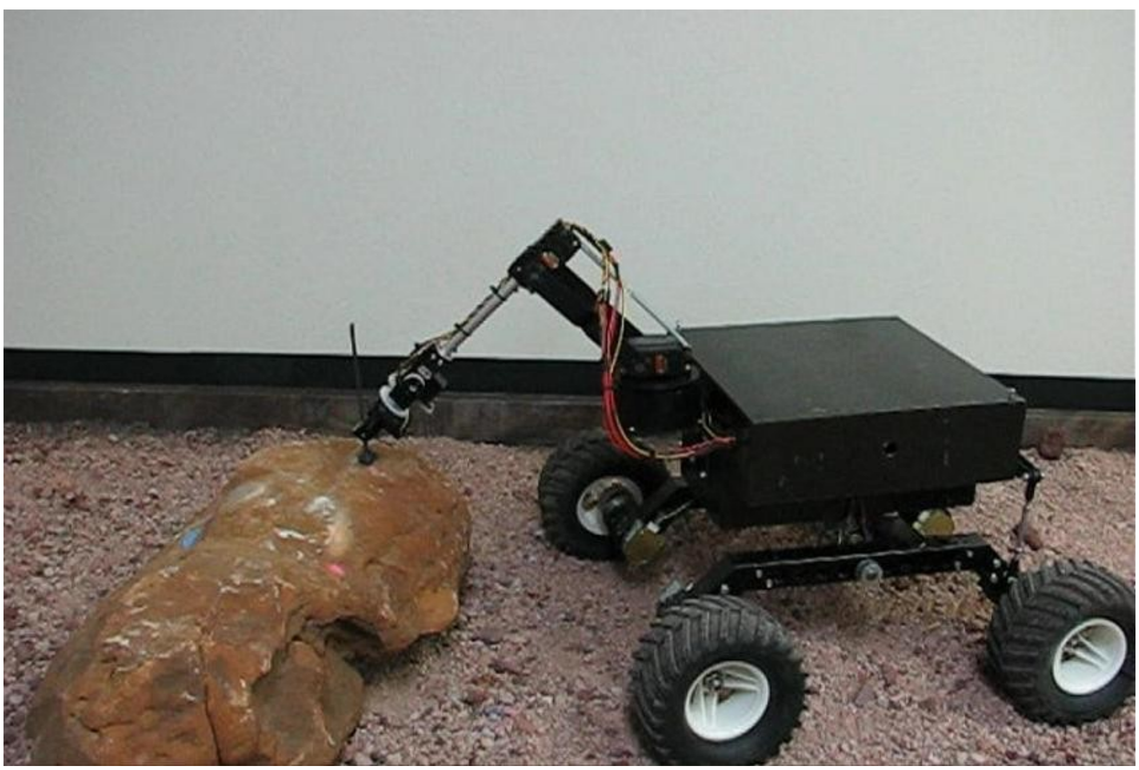

Figure 23. Healthy T-R-T serial chain

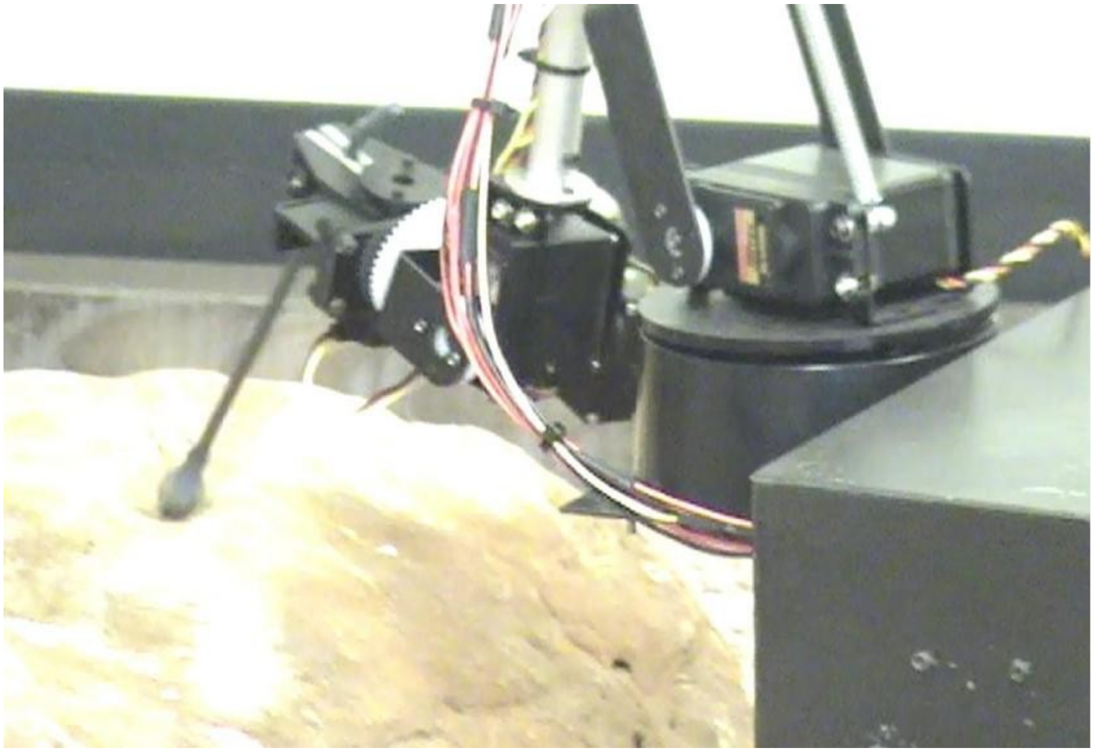

Figure 24. Crippled configuration TT of the TRT

5.8 Summary of the Test

The test for the Failure Recovery synthesis technique which was put forward by Robson and McCarthy [1] was discussed. To show the practical implementation of this technique, a Lynxmotion – AL5D robot arm and SMP platform was built. The arm was integrated onto the front of the platform and both were controlled through NI sbRIO 9632XT, as well as a SSC-32 controller. The simultaneous control of the robot arm and platform was made possible. The control units are keyboard for the platform and Logitech –ATK 3 Joystick for the arm. The failure recovery of the arm was demonstrated when the reposition parameters were passed into LabVIEW. This results in a new position for the base of the platform, the moving point of the arm and a new grasp point respectively in order for the rover to complete the originally specified task.

5.9 Comments

The present logic for simultaneous control of arm and platform operates in an open loop, but if the platform and arm operate in a challenging environment, autonomous navigation is to be considered.

The idea for the closed loop control can be made possible monitoring the distance moved by the platform. For this purpose, we integrated encoders to all four motors, which continuously update the count to the controller. Based on these encoder values, the controller decides which way to go further and supplies the required signals to the motors of the platform.

At present, we consider two degrees of freedom for the platform. As a result a two-axis compass HMC 6352 can be integrated. The benefit of this compass can be largely realized in the ability to make a perfect 90 degree turn from the current position. This helps us to turn approximately from a given ‘X-Direction’ to a given ‘Y-Direction’. Another issue beside the current implementation is the excessive movement of the robot arm when the platform is in motion, this can be due to the lightweight of the robot arm used in comparison to the mobile platform. Lastly, the present code considers the base of the platform to be in a plane, but in reality it exists in 3D space, which has to be accounted for.

6. DESIGN OF SPHERICAL MECHANICAL LINKAGES FOR REAL WORLD APPLICATIONS

The spherical linkages form an important class in Robot manipulators. Some applications of the design of spherical mechanical linkages for Power Assist and Cooperative movement of two robotic arms- TS and RRS application is presented below.

6.1 Power Assist Mechanism

The goal of the synthesis of this mechanism is to design a TS chain that provides power to assist humans to perform repetitive manufacturing operations. This mechanism can be of a great help in human therapeutic movement or when the humans experience weakness in their arms due to some health conditions. This mechanism is designed to guide patient’s arm through a set of task positions, while satisfying the velocities and accelerations and along a given trajectory as in Figure 25.

Figure 25. Power Assist for human therapeutic movement

The synthesis of this mechanism has certain requirements and specifications:

1. The mechanism is designed for the arm of the worker; TS chain must start and end at a certain position and follow the trajectory defined by the worker properly and smoothly. (See Figure 26.)
2. The mechanism discussed here is designed for the right arm of the worker; this arm is modeled as perpendicular RRS serial chain.
3. The lengths of the upper and lower arm are considered to be of the average lengths of all humans, i.e. about 29cms.
4. To prevent any untoward incident from happening, the mechanism is so designed that the body of the worker is taken into account into so called “protected zone”. Therefore, the trajectory which is to be followed is considered out of the area which encloses the body.

This protected zone is taken to be a rectangular solid to cover the maximum area. The coordinates of this rectangular solid are given beforehand while synthesizing the mechanism.

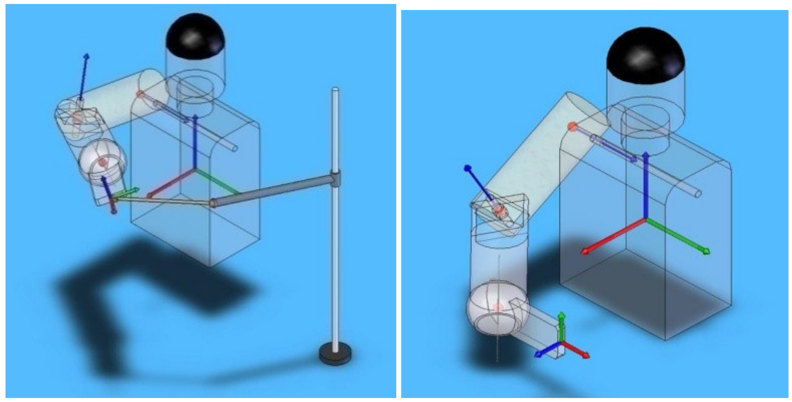

Figure 26. The arm of the worker and mechanism following a specified trajectory

The rectangular body of the worker has the following coordinates, given in the Table 7. in mm:

Table 7. Vertices of the body of the worker

Vertex 1	Vertex 2	Vertex 3	Vertex 4	Vertex 5	Vertex 6	Vertex 7	Vertex 8
-160	-120	-120	160	-60	-20	-20	-60
30	30	30	30	-100	-100	-100	-100
50	50	-50	-50	-50	-50	50	50

For simplicity, the axis of the TS chain or the pole from which the TS chain originates is considered about the Z-axis, about (0, 0, 1).

Problem Statement: The trajectory to be followed by the human arm is given. To synthesize and design a TS chain to follow the same originally specified trajectory, we need to know the parameters **B**, **P** and R. The point **B** is the base point of the TS chain along the pole; the point **P** is the wrist point of the TS chain, which is to be gripped by the RRS chain. The distance R is the distance between this base point **B** and the wrist point **P**. To ensure that the TS chain does not enter the body of the worker, the coordinates of the body are considered. The movement between the RRS and the TS arms need to be smooth and also follow the given trajectory smoothly in same point in space and time.

The human has two tasks to be met in the 3D space, the position, velocity and acceleration requirements are specified in the Table 8.

The first three parameters in the position requirement specifies the longitude, latitude and roll parameters to be satisfied, the last three parameters represent the translational X,Y and Z coordinates. The velocity and acceleration specifications define the first and second derivatives of these parameters respectively.

Using the synthesis algorithm mentioned in Section 2, we compute the parameters of the TS chain which satisfies the task requirements. The obtained parameters **B**, **P** and R for the given task are computed and are given in the Table 8.

Table 8. The solutions to the synthesis of TS chain for Power Assist mechanism

B [m]	**P** [m]	R [m]
(0.2772, 0.8050,0)	(0.101,-0.274,-0.476)	1.876

After planning, the animation shows the smooth movement of the arm and the designed TS chain. The TS chain synthesized is fixed to a pole, the body of the worker is assumed to be the rectangular portion, and trajectory is given in black, which is the common trajectory for both the TS and the RRS chains. The set of coordinates which are the end points of this trajectory represent the two positions which are to be reached by this system, with the required velocities and accelerations.

6.1 Synthesis of Parallel Mechanical Linkages

The goal of this synthesis is to design a TS chain, based on the inverse kinematics and path planning of a TRS chain, resulting in a closed loop TRS-TS mechanism. The task is pretty challenging, since the mechanism is constrained to have the same Base and Moving pivots. Here the aim of the two arms is not only to follow a common trajectory but also to have one and the same base pivot.

A task of two positions, two velocities and one acceleration is specified for both arms, using Vicon 3D motion capture system, available in our Human Interactive Robotics Lab. The positions, velocities and accelerations, imported from the motion capture system are given in Table 9. Using the algebraic synthesis procedure described in Section 2, the TRS and the TS arms have been synthesized for a given fixed pivot coordinates **B** = (-0.4563, -0.034, 0). The motion of the TRS mechanism was synchronized, such that the cooperation is smooth between the arms and the trajectory was followed by both arms simultaneously in space and time and is shown in Figure 27.

The trajectory that the TS chain needs to follow is specified by obtaining the inverse kinematics of the TRS arm, going through the originally specified task of two positions, two velocities and one acceleration. Mathematics animations, ensures the smooth synchronized motion of both arms through the originally specified task. It can be seen that this structure results in a closed loop parallel TRS-TS mechanical linkage.

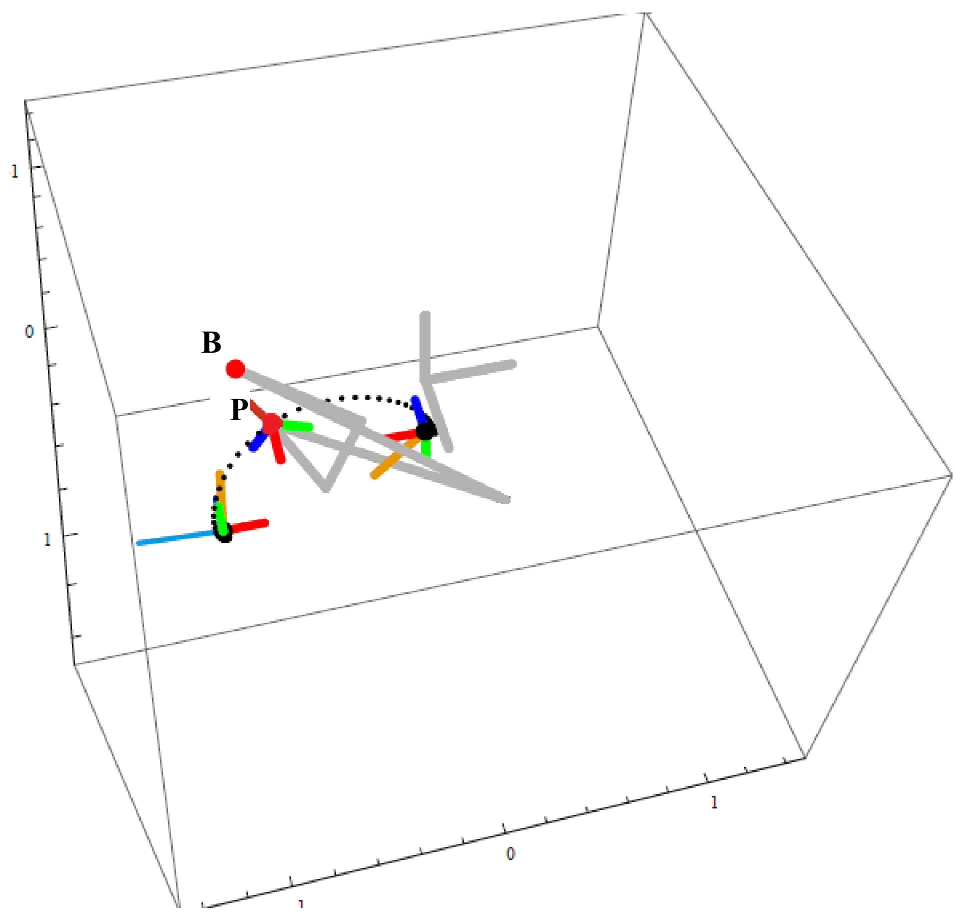

Figure 27. Synthesis result of Parallel Mechanical Linkages

The task specification for the above solution is given in Table 9.

Table 9. Task specification for the synthesis of Parallel Mechanical Linkages

Position (m)	Velocity (m/s)	Acceleration (m/s^2)
(0,-90 °,180 ,0.63,3.26,.013)	(0,0.1,0.3,0,-0.1,0.1)	------------- ----
(180°,90°,0,0.635,3.27,0.013)	(-.1,0,0,-.1,0.01,0)	(0,0.1,0,.3,.1,.1)

7. CONCLUSIONS AND FUTURE DIRECTIONS

The present research expands on Robson and McCarthy's [1], [2] recent works on synthesis techniques for the joint actuator failure recovery of robot manipulators, working in remote and challenging environments. Synthesis technique for the design of spherical mechanical linkages was presented and results were generated using Mathematica. The practical testing of the failure recovery technique, required an experimental set up. For this purpose, a Lynxmotion (AL5D) robot arm and the Surface Mobility Platform (SMP) were integrated into a system. The control logic was written in LabVIEW using different programs i.e. VIs. Simultaneous control of the robot arm and platform was obtained. The results of the failure recovery in case of elbow failure were generated and presented using the real physical system. The applications of the synthesis of spherical mechanical linkages were demonstrated into the design of Power Assist Mechanism and the design of parallel kinematic chains.

The research at present has some issues regarding the practical implementation of the failure recovery logic, specifically in the dynamics of the robot arm and the consideration of the base point in space. The present tests were conducted in an open loop control, but for the system to operate in challenging environment, it should have a feedback mechanism. For this purpose, a HMC 6352 magnetic compass could be integrated with the encoders to supply the coordinates of the positions of arm and the platform. The synthesis procedure was considered for the spherical mechanical linkages, which can be further extended to spatial mechanical linkages for use in a six degree of freedom arm like a TRS robot arm.

At present, only planar, two-dimensional movement for the platform was considered. As a result a two-axis compass HMC 6352 can be integrated. The benefit of this compass can be largely realized in the ability to make a perfect 90 degree turn from the current position.

Another task for future consideration is the excessive movement of the robot arm when the platform is in motion. This can be due to different reasons, one of which is the lightweight of the robot arm used in comparison to the mobile platform.

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APPENDIX A. ELECTRONIC SPEED CONTROLLERS

An Electronic Speed Control or ESC is an electronic circuit with the purpose to vary an electronic motor's speed, its direction and possibly also act as a dynamic brake. ESCs are often used on electrically powered radio controlled models.

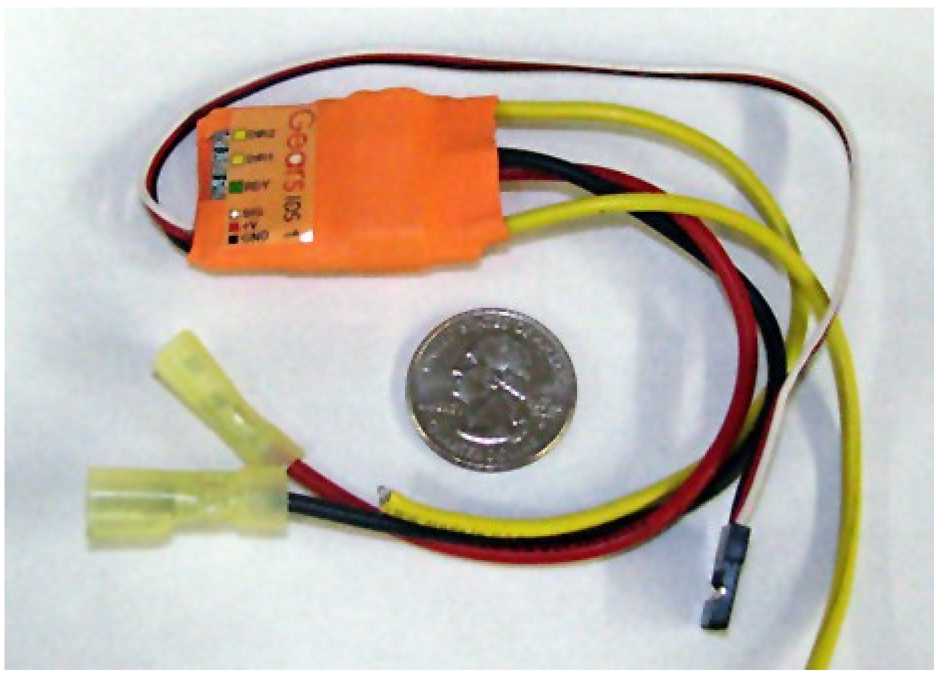

Figure 28. Electronic Speed Controllers

ESCs are needed for the smooth functionality of the motors. As shown in the Figure 28., the ESC is made with the four terminals, two for the power and two for two different directions, Dir1 and Dir2. These directions can be checked through the LEDs at Dir1 and Dir2.

These ESCs are chosen because of their lightweight for the purpose of start up and shut down of motors.

APPENDIX B. NI sbRIO 9632XT – REAL TIME CONTROLLER

This controller was funded by National Instruments Inc. NI sbRIO-9632/9632XT embedded control and acquisition device integrates a real-time processor, a user-reconfigurable field-programmable gate array (FPGA), and I/O on a single printed circuit board (PCB) as in Figure 29. It features a 400 MHz industrial processor, a 2M gate Xilinx Spartan FPGA,110 3.3 V (5 V tolerant/TTL compatible) digital I/O lines, 32single-ended/16 differential 16-bit analog input channels at 250 kS/s, and four 16-bit analog output channels at 100 kS/s. It has three connectors for expansion I/O using board-level NI C Series I/O modules. The sbRIO-9632XT provides an extended temperature range of-40 to 85 °C with 19 to 30 VDC power supply input range, 128 MB of DRAM for embedded operation, and 256 MB of nonvolatile memory for storing programs and data logging.

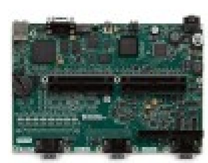

Figure 29. Ni sbRIO 9632XT

It has a built-in 10/100 Mbits/s Ethernet port used to conduct programmatic communication over the network and host built-in Web (HTTP) and file (FTP) servers.

You also can use the RS232serial port to control peripheral devices. The sbRIO-9632 is designed to be easily embedded in high-volume applications that require flexibility, reliability, and high performance

VITA

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