Hyper-Redundant Manipulator Control for Reconfigurability and Obstacle Avoidance

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Abstract

For manipulators to be an effective option in soft automation, they require redundancy and versatility. A typical application is motion in unpredictable surroundings such as foliage navigation in automated fruit picking. To date, centralized control architectures with real-time constraints have proven undesirable for the control of redundant systems. This paper uses a modular decentralized technique to demonstrate control of a redundant manipulator system. Advantages of the proposed approach are illustrated through redundancy, reconfigurability and fault tolerance. Results in simulation show dynamic motion path generation and obstacle avoidance capabilities in unmapped environments.

1 Introduction

Manipulators have primarily been limited to hard automation applications in industry due to their task-specific designs. For manipulators to be an effective option in unmapped environment negotiation, they require redundancy and must be versatile enough to be capable of motion in unpredictable surroundings. Constrained environment applications, requiring the motion of such a manipulator, include nuclear reactors [Mclean and Cameron, 2003] and foliage navigation in automated fruit picking [Sarig, 1993]. To date, research has largely focused on offline control requiring significant path planning time and a known static environment for negotiating obstacles [Ahuactzin and Gupta, 1995].

The shift from hard automation became feasible with the implementation of a rapidly deployable manipulator system [Paredis *et al.*, 1996] in designing and constructing a Reconfigurable Modular Manipulator System (RMMS). RMMS was also capable of developing its own inverse kinematics once a system configuration was constructed, using a real time algorithm [Kelmar and Khosia, 1990; Schmitz, *et al.*, 1989; Kelmar and Khosia, 1988]. The use of multiple processors, working in a modular framework communicating with a central processor, presents real-time co-ordination difficulties [Yamakita, *et al.*, 2003; Matsuno and Suenaga, 2003] constraining system controllability. For increased redundancy, the modeling and design procedures become more complex. This results in more complex algorithms which increase computational delays, again complicating the systems controllability. To control redundant reconfigurable systems, it has been found that decentralized control architectures are desirable [Yook, *et al.*, 1997].

Current research in multi-robot systems has produced frameworks for team motion co-ordination as well as novel communication methods for self-reconfigurable robots [Shen, *et al.*, 2002]. The Adaptive Distributed Control (ADC) protocol produces hormone like messages used to produce locomotion in dynamic reconfigurable environments. Further work on multi-robot systems has also been undertaken using a neural oscillator as a central pattern generator to create system motion [Kamimura, 2003]. These methods allow for an effective and novel means of communication between connected modules.

The implementation of a reconfigurable modular manipulator raises a further problem as to how the manipulator relates to its newly acquired immediate environment. Researchers in multi-robot systems are currently addressing such issues, investigating the co-operative multi-robot behavior to flock, disperse, aggregate, forage, collectively explore environments and follow trails [Arai, *et al., 2002*]. Research in this field is however theoretical with little practical application [Jantapremjit and Austin, 2001].

NASA has produced manipulators for inspection purposes with both redundancy and high dexterity [Marzwell and Slifko, 1995; William II and Mayhew IV, 1997]. There are three major approaches for solving the redundancy problem in controlling redundant manipulators [William II and Mayhew IV, 1997; Baillieul, 1985; Liegeois, 1977; Chernousko, *et al.*, 1994]. The universal requirement of the approaches is a predetermined end effecter trajectory [Zlajpah and Nemec, 2002]. Though these approaches allow for the manipulator's negotiation around obstacles they are conditional on the undisturbed motion of the end effecter along the predetermined trajectory. This is especially unfavorable for obstacle avoidance in unmapped environments.

In this paper, redundant system controllability is investigated using the Modular Decentralized Control (MDC) approach. This approach utilizes the physical modular link layout of a redundant manipulator allowing multiple link(module)-embedded processors to work to achieve a common goal. The advantages of the approach are concurrent redundancy control, system reconfigurability and real-time obstacle avoidance without a predetermined end effecter trajectory, achieved through decentralized control.

The MDC approach is explained in section 3. Section 4 provides numerical examples demonstrating the reconfigurable, fault tolerant and obstacle avoidance capabilities of the control approach. Findings on the manipulator's motion profiles are discussed in section 5.

Figure 1. Physically Constructed Module

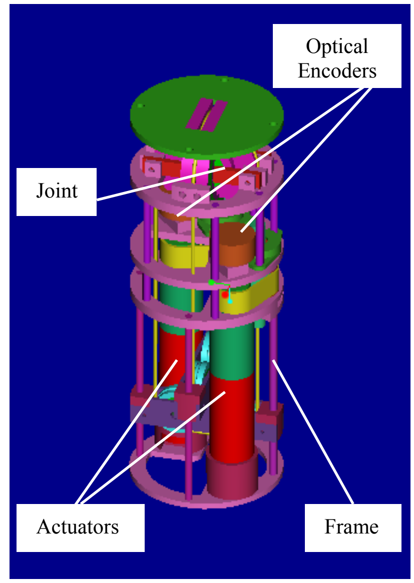

Figure 2. CAD Drawing of Module

2 Modular Hyper-Redundant Manipulator

Figure 1 shows a modular manipulator system to be used as a real world application of the proposed control approach. The manipulator has been designed with each link enclosed within a modular structure including mechanical actuators, microprocessors and motor controllers. Physical flanges at both ends for the module allow for ease in system reconfigurability. Figure 2 shows the designed hyper-redundantant manipulator module with their external casings removed. Each module has two rotational degrees of freedom, allowing for module orientation about its base as determined within the module's internal controller.

The manipulator design allows for a maximum of five links to be connected in a serial arrangement. Each module can communicate through recieving and transmitting data between the directly adjacent lower and upper modules in the series.

The modular number limitation of the designed manipulator is determined by the mechanical constraints of the manipulator as given in Table 1. The decentralized control method has been found not to limit the number of modules in the manipulator structure.

Module Parameter	Value
Rotational Degrees of Freedom	2 (About x and y)
Min. Length / Diameter	$205mm/76mm$
Mass	$1.05kg$
Maximum Angular Rotation	$\pm 40\deg.$
Maximum Angular Velocity	$40\deg./s$
Maximum Angular Acceleration	$200\deg./s^2$

Table 1. Manipulator Module Properties

The end effecter is mounted with a sterio vision camera on the free end module of the manipulator. This allows the end effecter to determine the 3-dimensional displacement between the desired position, ${}^{N}\overline{x}_d$ and the current position of the end effecter, ${}^{N}\overline{x}_a$ as required for broadcasting through the modules for the decentralized control of the manipulator.

Proximity sensors have been mounted on the external casing of each module allowing for the individual modules to detect any objects in their close proximity.

The designed manipulator is tailored for reconfigurable systems and built on the premise that system flexibility is obtained by independent control of modules with limited interaction.

3 Modular Decentralized Control

In this section, the modular decentralized control method to be implemented for the above reconfigurable hyper-redundant manipulator system is addressed. The decentralized control method allows each link to act independently of other links. The method suggests the possibility of a modular approach of cloned links to achieve system controllability. This allows for the elimination of a CPU's need to model and control the complete redundant manipulator, with an infinity of solutions. Further, this approach utilizes the concept of modular manipulator systems to allow multiple link embedded processors to work to achieve a common goal, demonstrating a bottom-up approach to manipulator control.

The links controlling inputs, viewed in the local link's frame of reference both actuator orientations is

$$\overline{\theta}_i = \begin{bmatrix} \theta_{x_i} \\ \theta_{y_i} \end{bmatrix} \qquad (1)$$

As two axes of rotation exist for each link, rotation occurs around the y-axis first following by rotation around the x-axis.

Module data is self-contained with module proximity sensor identification of any close obstacles. The modelled links are further composed of:

- Two single axis rotating actuators ($\pm 180^o$)
- Mechanical flanges at each end of the link
- I/O communication ports at each end of link

3.1 Serial System Layout

The manipulator's control is laid out such that each link's embedded microprocessor independently determines its motion profile. However, as links are physically connected in a serial structure, shown in Figure 3, the distribution of information within the manipulator, from module to module, is arranged to utilize this structure. It is noted, that though the physical layout of the manipulator is serial and the data distribution between modules utilizes the serial nature of the manipulator, the underlying control of each module is independent of other modules, presenting a decentralized control system.The serial layout, also demonstrates that the modularly controlled system does not require knowledge of the base connection. This lack of base reference enables links in the manipulator to be added or removed from the system without modification of system controllability.

3.2 Redundant System Control

When the goal is recognized by the end effector's stereo vision and its relative position, ${}^{n}\overline{x}_d$ is known, each module's prime objective is it to position the common point, namely the end effecter, to the desired position.

In so minimising the respective approach angles for each module the manipulator can provide such motion for the end effecter as required to reach the goal [Vittor, *et al.*, 2003]. The angles that are minimized are shown in Figure 3 where the respective angles are $\overline{\theta}_1, \overline{\theta}_2, ..., \overline{\theta}_{N-1}, \overline{\theta}_N$. Each module recieves and transmits the current position of the end effecter and the goal position for the end effecter.

Though the end effecter to goal 3-dimensional displacement is identical for all modules the observing frame of reference differs based on the modules position in the manipulator.

For a module's local inputs, ${}^{i+1}\overline{P}_a, {}^{i+1}\overline{P}_d$ from its successive link $(i+1)$. Using the functions

$$ {}^{i}\overline{P}_a = {}^{i+1}_{i}\underline{T}_{\left({}^{i+1}_{i}\theta_x, {}^{i+1}_{i}\theta_y, l_i\right)_i} {}^{i+1}\overline{P}_a \qquad (2) $$

$$ {}^{i}\overline{P}_d = {}^{i+1}_{i}\underline{T}_{\left({}^{i+1}_{i}\theta_x, {}^{i+1}_{i}\theta_y, l_i\right)} {}^{i+1}\overline{P}_d \qquad (3) $$

the controlling inputs in the i^{th} link frame of reference are found. The desired and actual end effecter positions are then used to determine the rotational goal, in the individual link's frame of reference.

$$ \theta_{x_i} = \tan^{-1}\left(\frac{{}^{i}y_d}{{}^{i}z_d}\right) - \tan^{-1}\left(\frac{{}^{i}y_a}{{}^{i}z_a}\right) \qquad (4) $$

$$ \theta_{y_i} = \tan^{-1}\left(\frac{{}^{i}x_d}{{}^{i}z_d}\right) - \tan^{-1}\left(\frac{{}^{i}x_a}{{}^{i}z_a}\right) \qquad (5) $$

$$ \text{for } i = 1,2,..., N-1, N $$

For converting the inverse tangent output from the (0,360) range to (-180,180) range the following transformation is used.

$$ \theta = \begin{cases} \theta + 360 & if \quad \theta < -180 \\ \theta & if \quad 180 \geq \theta \geq -180 \\ \theta - 360 & if \quad \theta > 180 \end{cases} \qquad (6) $$

Each link then provides actuator motions to reach the above rotational goals.

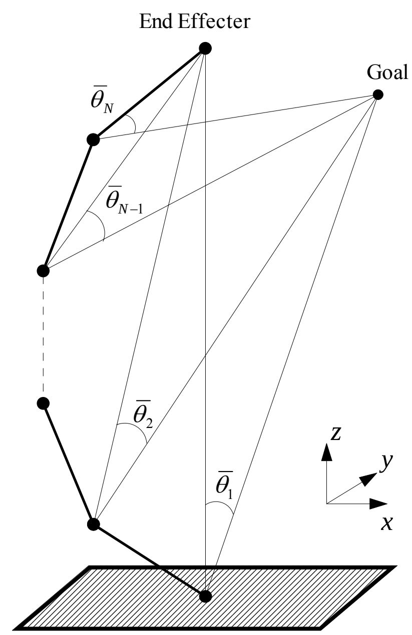

Figure 3. Local Goal Approach Angles

3.3 Obstacle Avoidance

In the presence of obstacles, the manipulator's path can now be locally altered utilizing the decentralized control of the manipulator. Obstacle avoidance is achieved by each link when it observes an obstacle in its vicinity. It then provides motions in its local actuators so as to move away from the obstacle. Where individual link motions are insufficient for avoiding an obstacle, motion avoidance procedures of successive links can be activated through broadcast messages, furthering the collision avoidance capabilities of a manipulator.

The avoidance procedure of links provides means whereby the end effecter may move away from the goal position temporarily. This requirement avoids traps in local minima, allowing the manipulator more freedom of motion to navigate around obstacles.

4 Numerical Examples

A simulation in MATLAB Simulink was produced to demonstrate the practicality of the MDC approach to be inplemented in the manipulator. In the simulation, each link knows its own angular offsets from its nearest neighbors and the distance from the end effecter to the goal position in its own frame of reference. The links are physically connected in series though they function independently and work in parallel to achieve the overall goal. The simulation layout limits information flow to one direction from the end effecter to the base.

The link properties include two DOFs per link, which allows movement on the surface of a sphere. Communication between successive links and embedded processors on individual links takes place as shown in the link schematic in Figure 3.

The two examples shown in this paper are reconfiguring modules and obstacle avoidance. Six 100 mm notional links are used by way of demonstration. In the simulation, an initial condition goal relative to the base ${}^{b}\overline{x}_d$ is constant, where

$$^{n}\overline{P}_a = {}^{1}_{0}\underline{T}^{-1}\,{}^{2}_{1}\underline{T}^{-1}\cdots{}^{n-1}_{n-2}\underline{T}^{-1}\,{}^{n}_{n-1}\underline{T}^{-1}\,{}^{b}\overline{P}_a \qquad (7)$$

$$^{n}\overline{P}_d = {}^{1}_{0}\underline{T}^{-1}\,{}^{2}_{1}\underline{T}^{-1}\cdots{}^{n-1}_{n-2}\underline{T}^{-1}\,{}^{n}_{n-1}\underline{T}^{-1}\,{}^{b}\overline{P}_d \qquad (8)$$

The above equations are used to represent the stereo vision ${}^{n}\overline{P}_g$ data in the simulation, as given by

$$^{n}\overline{P}_g = {}^{n}\overline{P}_d - {}^{n}\overline{P}_a \qquad (9)$$

4.1 Reconfigurable Modules

This section provides two examples where the manipulator's structure is altered and then controlled to achieve a given goal. It is to be noted that after reconfiguration of modules, no re-compilation of the system is required.

Figure 4a shows the normal successful motion of a regular manipulator instructed to move from the initial condition (-600,0,0) to the goal, set at (300,300,350).

The first change instituted to demonstrate the reconfigurable nature of the control approach is to replace the third link from the base with a link of a different length, now 300mm. By keeping all other parameters constant and without informing other links of the change, the manipulator was again instructed to reach the goal position (300,300,350). Figure 4b shows the resulting motion profile of the manipulator in successfully reaching the same set goal.

The second change instituted nominates failure of one link during motion. The system attempts to reach a given goal, but one link's capability is lost. The demonstration shows the ability of the MDC to circumvent the fault when moving to a goal. The link closest to the end effecter was caused to fail some time into the goal-seeking routine. Figure 4c shows the resulting motion profile of the manipulator in again successfully reaching the set goal.

In the plots, shown in Figure 4, no optimization of the manipulator's motion profiles have been used through the use of varying time constants in each links.

4.2 Obstacle Avoidance

An advantage of using a redundant manipulator in reaching a goal is its obstacle avoidance potential. This section demonstrates an example whereby a six link 12 DOF manipulator approaches a goal (150,0,500) while avoiding two obstacles. The initial condition of the manipulator places the end effecter at (450,0,386) as shown in Figure 5a. The obstacles used are two bars with coordinates (-200,-300≤y≤300,300) and (0,-300≤y≤300,150).

For avoiding obstacles, the method employed in this simulation is that each link's proximity sensor is activated when an obstacle reaches a cylindrical shell of radius 50 mm centered on the axis of the link. The manipulator link provides an actuator motion so as to repel itself from the obstacle in the shortest possible path moving away from the obstacle.

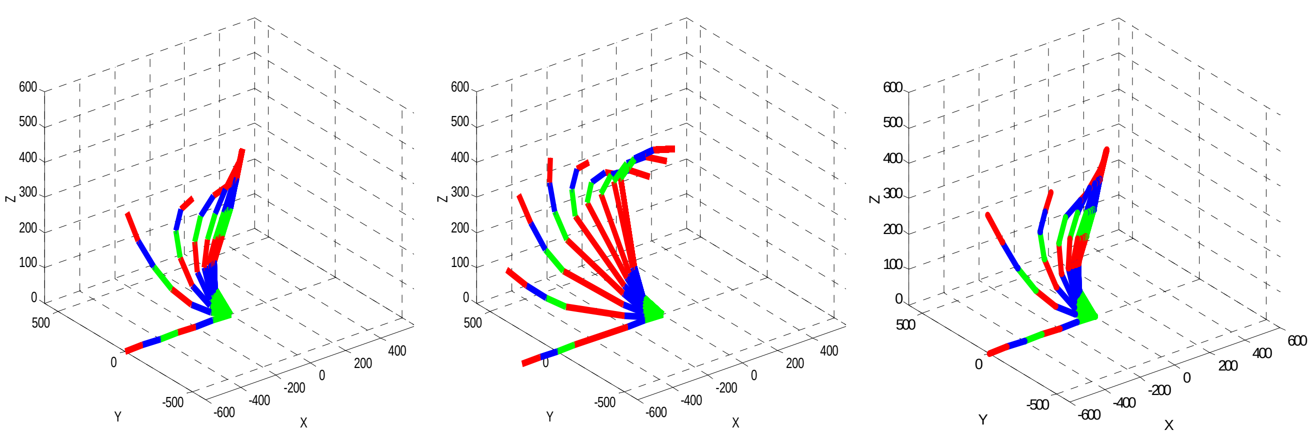

Figure 4. Successful Manipulator Motion Paths a) Unaltered b) Replaced third link c) Link failure during motion

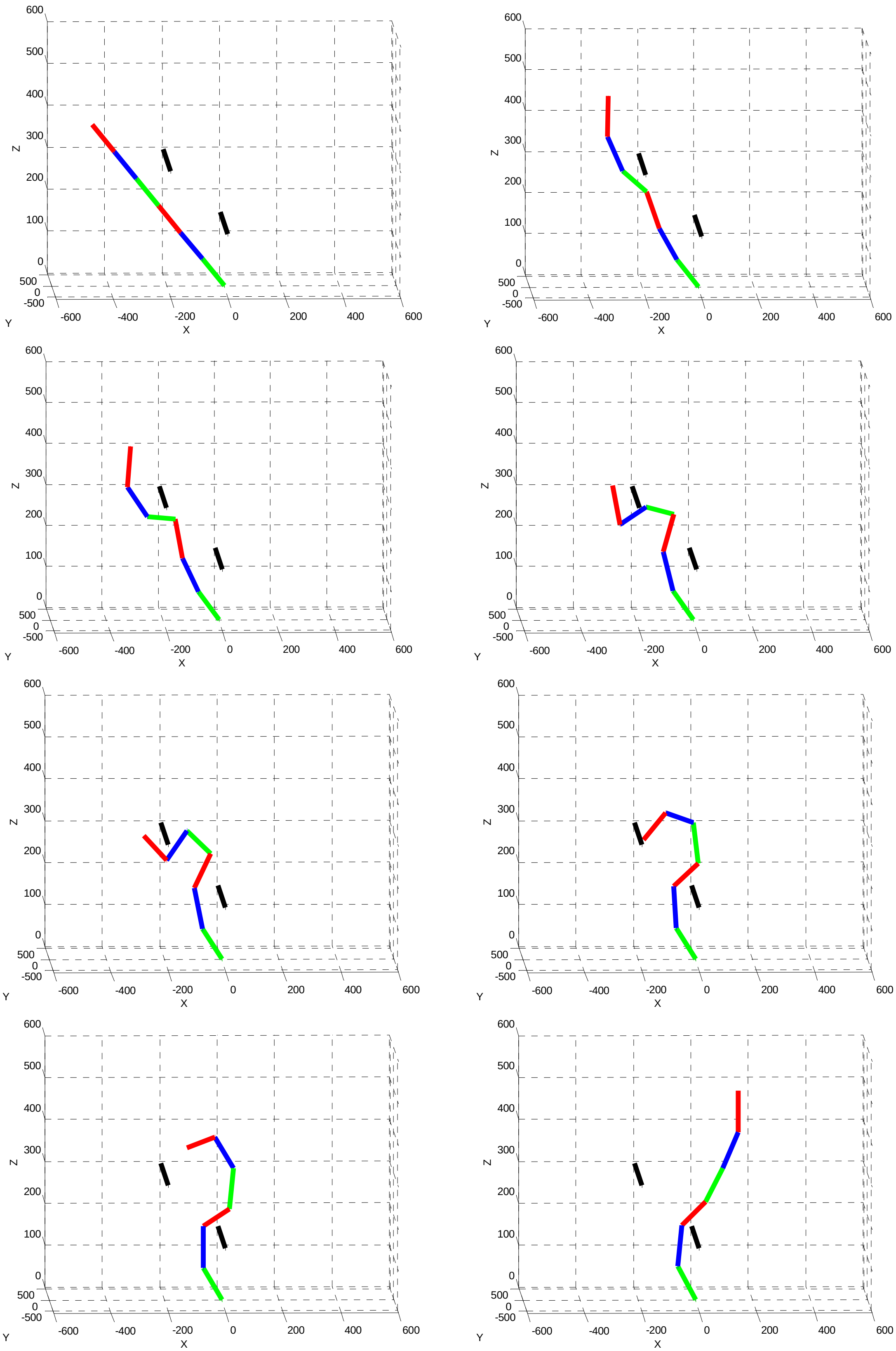

Figure 5. Obstacle Avoidance Sequence: a) Initial conditions b) First attempt to reach goal c) to f) Obstacle negotiation g) Approaching final position h) Final position reached.

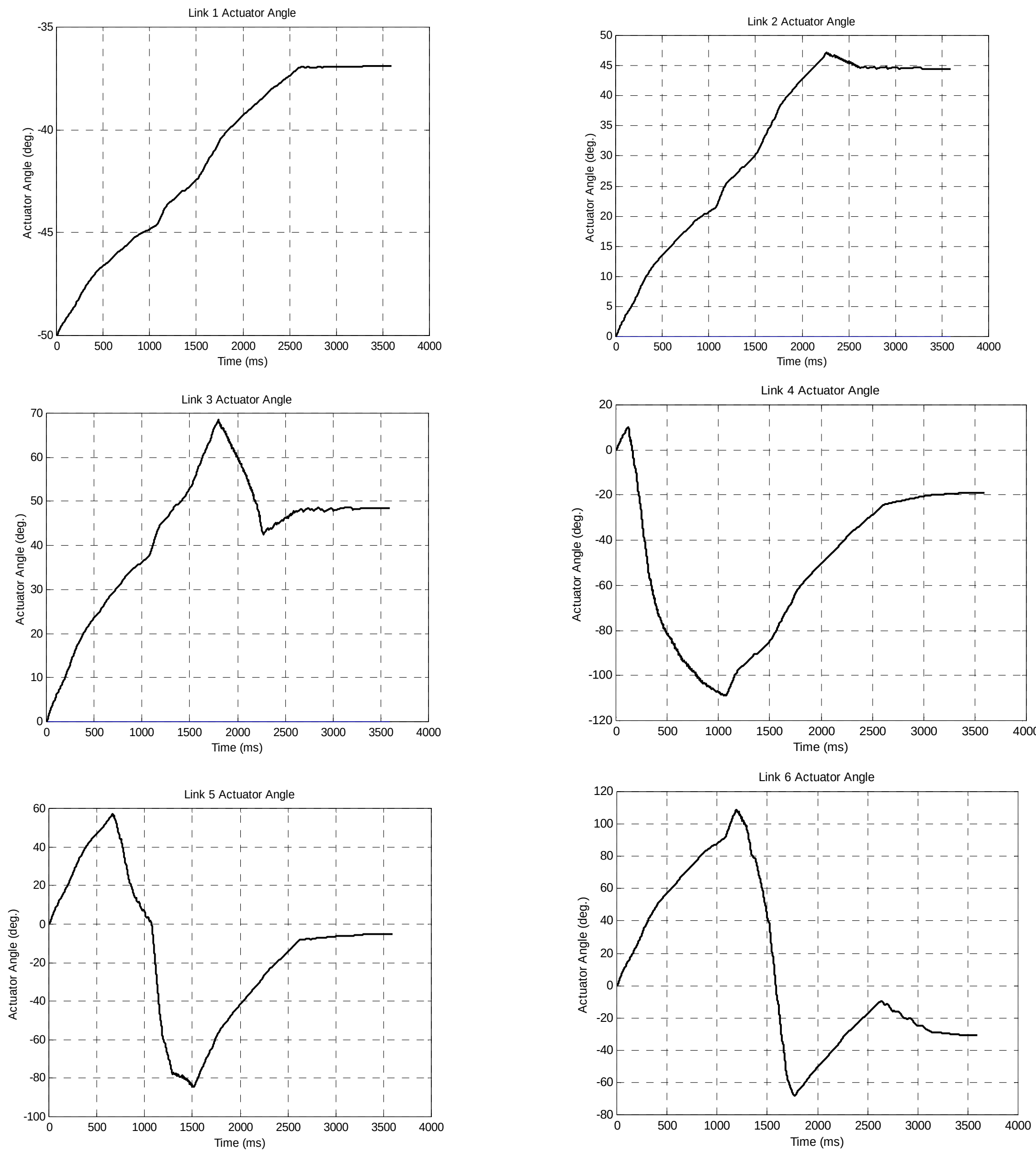

Figure 6. Link Actuator Motion Profiles

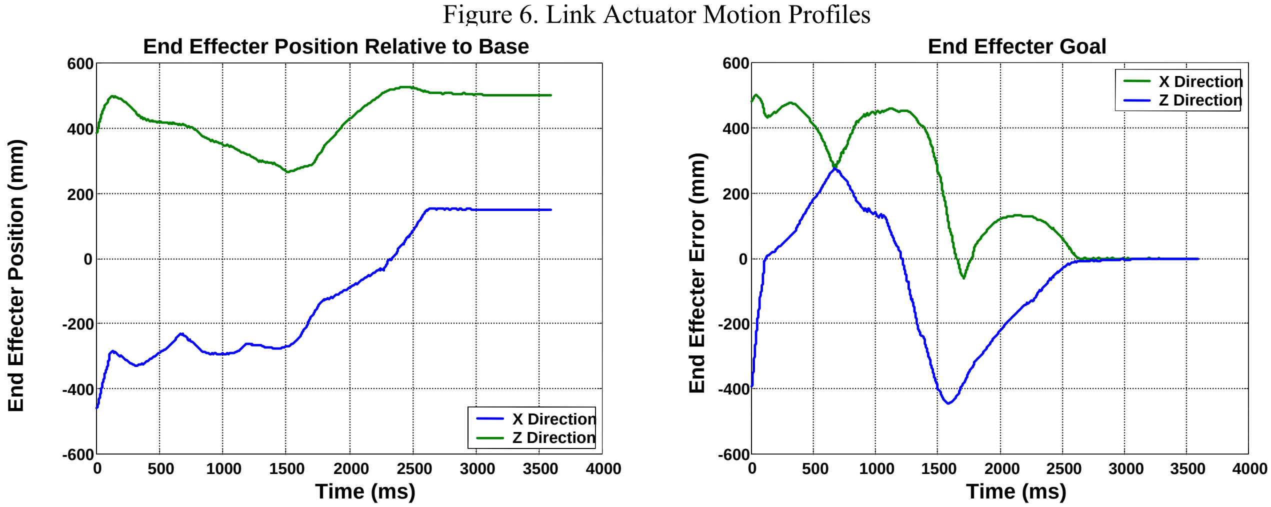

Figure 7. End Effecter a) Position Relative to Base b) Goal

The function used for obstacle avoidance in this simulation is

$$\left[\theta_{x_i}, \theta_{y_i}\right]_{g\ new}^T = 2 \cdot (q - 0.5) \cdot \left[\theta_{x_i}, \theta_{y_i}\right]_g^T \qquad (10)$$

where $q = 1$ when proximity sensor idle and $q = 0$ when proximity sensor activated

In this simulation, heuristic optimization of the manipulator's motion was achieved by modifying the time constants of the first order response of each link. The shortest time constant was given to the link nearest to the end effecter, incrementally increasing by a factor of 1.2 per link moving to the base.

Figure 5 shows the motion profile of the manipulator successfully negotiating the two obstacles and reaching the set goal.

4 Discussion

Figure 4b shows the reconfigurable capabilities of the decentralized control approach where manipulator design can be altered through the introduction of modules with irregular properties depending on application requirements. These links contain self-reliant data, acting as plug-and-play components in the manipulator system. The redundant nature of the manipulator further allows for fault tolerance as shown in Figure 4c. If link failure occurs, the remaining modules individually accommodate changes, dynamically providing a means for reaching the goal. The manipulator's paths intuitively appear close to optimal for each scenario, dynamically adjusting to accommodate for system changes.

The obstacle avoidance scenario in Figure 5 shows how the manipulator negotiates obstacles, successfully reaching the set goal. It is noted that the decentralized control allows for the end effecter to temporarily move away from the goal when negotiating obstacles.

The serial layout of the manipulator provides a means of determining motion around obstacles. Where the obstacle is near the base of the manipulator, the links attempt to reach the goal by orientating around the obstacle. However if the goal is a significant distance from the base of the manipulator, the base links will drive the manipulator past the obstacle, retracting the end effecter first rather than wrapping around the obstacle.

Experimentation with manipulator time constants revealed that it was advantageous for the end effecter proximate links to be more responsive then those nearer the base. This enabled the end effecter to be in transit to the goal before links near the base had opportunity to take affect, in order to favor line of sight movement of the end effecter relative to the goal.

The independent motion of each link actuator can be seen in Figure 6 with desired motions hindered where links avoid an obstacle. The sequential avoidance of the obstacle at (-200,-300≤y≤300,300) by links 4, 5 and 6 are manifested by non-monotonic actuator velocities in respective motion profiles. These procedures are coupled, e.g. link 4 and link 5 avoid the obstacle simultaneously.

Similarly avoidance of the obstacle at (0,-300≤y≤300,150) by links 2 and 3 also involves non-monotonic actuator velocities.

Figure 7a shows the position of the end effecter relative to the base and relative to the goal. Though some individual actuator motion characteristics are evident, the elicitation of the required individual link motions is not evident. The end effecter goal in Figure 7b, which is used to drive the links, shows distinct non-monotonic behavior, which normally only occurs with complex centrally controlled systems. This has been achieved simply by decentralizing the motion control.

The changes in motor directions as observed in Figure 6 may appear at first undesirable e.g. link 6 angles returning close to their original values. When viewing the overall motion in Figure 5 such behavior is desirable in finding a smooth path around the obstacles to the goal.

5 Conclusions

In this paper, the control of redundant manipulators is investigated using a MDC approach. This approach utilizes the physical modular link layout of a redundant manipulator allowing multiple module-embedded processors to work to achieve a common goal.

The proposed approach is applied to a 12 DOF six link redundant manipulator. Three examples are shown to demonstrate interchangeable links, link failure and the real-time negotiation of two obstacles in reaching a goal.

Numerical results indicate that the control approach readily accommodates system reconfigurabilty, dynamically adjusting motion utilizing the flexibility of the complete manipulator. This presents capabilities for robust control of a redundant manipulator in an unmapped environment without a predetermined end effecter trajectory.

6 Future Work

Much scope exists for future work in the optimization of decentralized control theory, as much in the choice of redundant manipulator application as in the broad research field of redundant system control.

Further motion profile optimization of the manipulator's MDC obstacle avoidance is to be investigated through the introduction of distributed sensor techniques.

Work is currently well advanced in making a modular arm with which to demonstrate autonomous fruit picking.

7 Nomenclature

${}^{i+1}_{i}\theta_x, {}^{i+1}_{i}\theta_y$ - Rotational angles about respective x,y axes between successive manipulator links i and $(i+1)$.

${}^{i}\overline{P}_a, {}^{i}\overline{P}_d$ - Current and desired position of end effecter as viewed in the i^{th} link's local frame of reference.

$\theta_{x_i}, \theta_{y_i}$ - Desired changes in rotational angles about respective x,y axes as viewed in the i^{th} link's local frame of reference.

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