Modular Decentralized Control of Fruit Picking Redundant Manipulator

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Abstract

Industry requires automatic fruit picking due to increasing labour costs and human variability in picking skill. This requires motion of a manipulator in unmapped dynamic environments that has hyper-redundancy to find its way successfully through leaves and branches. This paper uses a modular arm technique to generate kinematic redundancy in constructing and controlling a fruit picking arm that can navigate in such a flexible manner. The need for a full environment reconstruction in one master controller is bypassed by having localized sub-goals for each module. Decentralized control of the arm assists modular construction and selecting among the hyper-redundancy infinity of solutions. Singularities are avoided if the length of the deployed arm is greater than the distance to the object. If not, then the arm will point directly at the object and measure the shortfall in distance. The computational burden is kept down by restricting inverse kinematics to within each module. Results show stable controlled movement of the end effecter from multiple starting positions covering all possible approaches to the goal.

1 Introduction

The use of robot harvesters has been of keen interest in the Agriculture industry for many years [Tillet, 1993]. As demand for efficient harvest quantities increases, the use of human labour for harvesting has largely been superseded by the use of mechanised methods. Although many fruit growers have adopted these mechanised methods, their indiscriminate handling of fruit is an ever-present limitation. This limitation results in some harvested fruits being unsuitable for high quality picking, leaving the fresh fruit market to be mainly supplied by fruits picked by hand.

The desire to pick soft fruit suitable for fresh markets has in the last ten years been envisioned through the use of robots to simulate the human picker. With recent advances in robotics, this drive is becoming a feasible option.

In the 1980's, primary research was carried out to determine system capabilities required to harvest fruit more efficiently than an experienced human picker. Significant work has since been done in the production of end effecters, e.g. "MAGALI" in France [Rabatel, 1988] capable of harvesting apples and "CITRUS" in Spain [Pl'a *et al.*, 1993] for harvesting oranges, as well as dual arm harvesting robots [Recce *et al.*, 1996]. The limitations of these systems were mainly in their inability to locate fruits not immediately visible on the external canopy, as well as their inability to avoid obstacles while penetrating the canopy and picking a fruit. This resulted in robots being incapable of harvesting more than 75% of the potential fruits crop. One documented success rate has been 50% for apples [Sarig, 1993]. This limitation remains for open field harvesting, which has been attempted with only limited success for grapes, oranges, apples, watermelon and melon [Kondo and Ting, 1998].

To alleviate the problems of fruit recognition, research has turned to focus mainly on the use of harvesting robots in controlled greenhouse environments. Robots such as "CUPID" in the Netherlands [Henten *et al.*, 2002; Gieling *et al.*, 1995] and an Eggplant-harvesting Robot in Japan [Hayashi *et al.*, 2002; Hayashi *et al.*, 2000] have showed increased harvesting efficiency characteristics. Though the use of closed favorable environments allowed for improved fruit picking, it failed to address the main issue of manipulator's inability to negotiate foliage in harvesting fruit.

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 foliage negotiation, they require redundancy and must be versatile enough to be capable of motion in unpredictable environments. This has become 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 system was successfully implemented in a serial N-link DOF reconfigurable manipulator. This made the modular reconfigurable robot advantageous in making a system adaptable to different given tasks and unknown environment. NASA has produced manipulators for inspection purposes with both redundancy and high dexterity [Marzwell and Slifko, 1995; Williams II and Mayhew IV, 1997]. The major limitation of its design is its inability to negotiate obstacles in unmapped environments and has sporadic end effecter motions, both of which are undesirable.

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 *et al.*, 2001].

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]. This is known as an Adaptive Distributed Control (ADC) protocol that produces hormone like messages used to produce locomotion in dynamic reconfigurable environments. The protocol is distributed and fault tolerant, allows for collaborative behavior, asynchronous coordination and scalability. The limitation of the protocol is that only one hormone can be acted on at a time and numerous rule bases are required in each module for the various motions. This method allows for an effective and novel means of communication between connected modules.

The field of robot applications to date has largely been dominated by the requirements of high stability, high speed and precise movement. As robot functions have evolved from controlled stable applications to dynamic uncontrolled environments, the desire to incorporate redundancy to the above requirements has become essential. Kinematic redundancy is favorable in robots as it allows increased dexterity, versality and collision avoidance capabilities. Though numerous applications have been established where kinematic redundancy is considered favorable, the kinematic control of such systems remains a problem, with cross couplings between actuated motions.

In this paper, the nature of redundant system controllability is investigated, and whether it can be improved through the exploitation of the mechanical systems layout and decentralized control modeling. To deal with the redundancy problem in manipulators, two approaches, namely the centralized and decentralized methods, have been dealt with. The first approach imposes constraints on the system, thereby reducing redundancy, but still for singularity to occur. This method is commonly referred to as the "extended Jacobian method" [Baillieul, 1985]. The second approach limits redundancy by constraining the end effecter motion to a prescribed path. Overall motion is achieved by minimizing the motion of individual actuators to achieve either local optimization as in [Liegeois, 1977] or global optimization as in [Chernousko, *et al.*, 1994].

2 Modular Decentralized Control

As mentioned above, the means of describing mechanical manipulator systems can be portrayed in two methods as shown in Figure 1.

2.1 Centralized Method

The centralized method, a top-down approach, regards the motion of each actuator as determined by a central processor. Stereo vision is used to determine ${}^{n}\overline{x}_d$, the 3-dimensional displacement between the end effecter and the goal. This error is transformed using inverse kinematics to find the desired end effecter position relative to the manipulator's base co-ordinate system.

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

where

$$ {}^{i}_{i-1}\underline{T}^{-1} = \begin{bmatrix} C_{y_i} & S_{y_i}S_{x_i} & S_{y_i}C_{x_i} & 0 \\ 0 & C_{x_i} & -S_{x_i} & 0 \\ -S_{y_i} & C_{y_i}S_{x_i} & C_{y_i}C_{x_i} & l_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2) $$

$$ C_{x_i} = \cos(\theta_{x_i}) \qquad , C_{y_i} = \cos(\theta_{y_i}) $$
$$ S_{x_i} = \sin(\theta_{x_i}) \qquad , S_{y_2} = \sin(\theta_{y_i}) $$

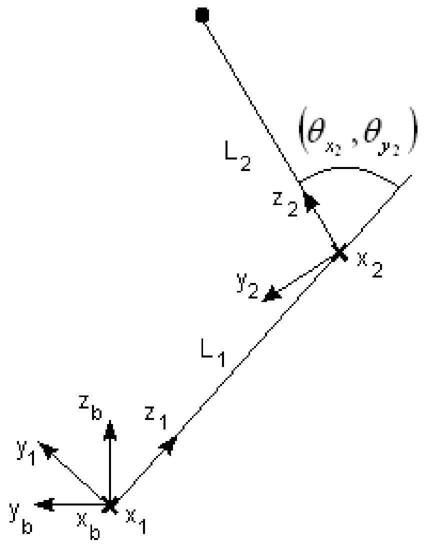

Figure 2. Transformation between links

The transformation shown in Figure 2 is used to find the general 2 DOF co-ordinate transformation between successive links in this paper assuming rotation about the x and y axes [Craig, 1989].

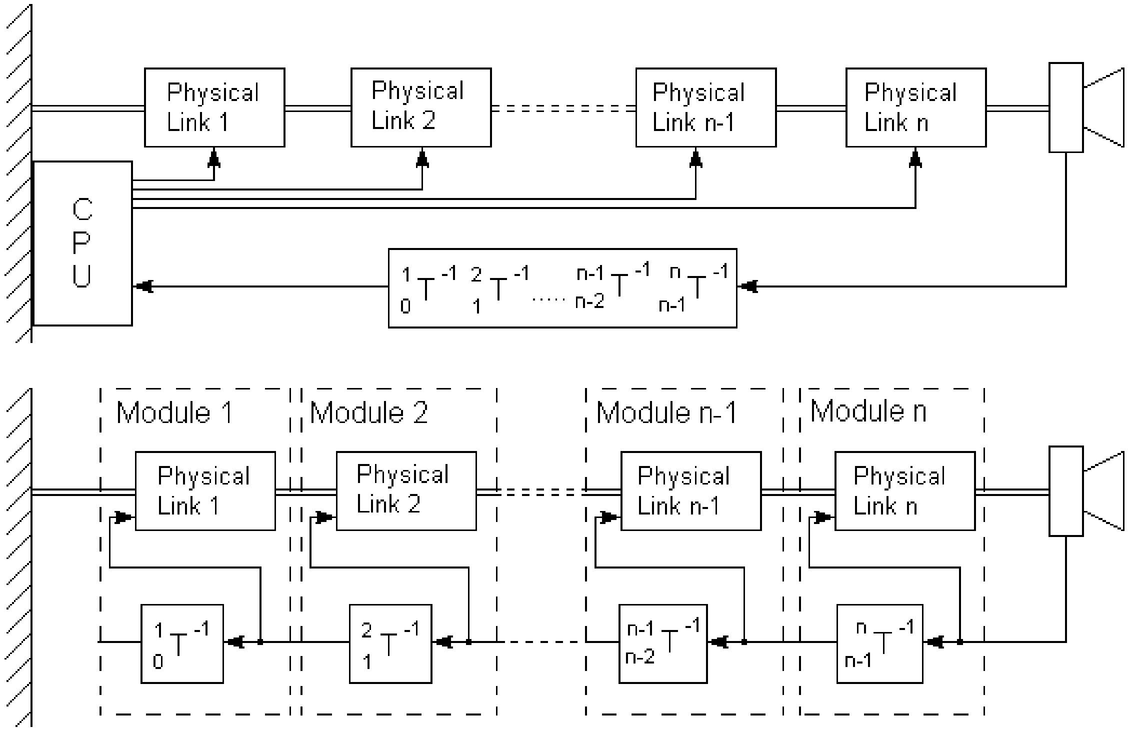

Figure 1. Redundant Manipulator Mechanical System Layouts

Using the above transformation, it is possible to produce a complete transformation matrix from the end link to the manipulator base. However, even though the inverse kinematics can be found by matrix inversion, it fails to provide an unique solution, there being a choice of two. The centrally controlled system based on a function $f_1(\cdot)$ where $n \geq 2$ links namely,

$$\left[\theta_{x_1},\theta_{y_1},\ldots..,\theta_{x_n},\theta_{y_n}\right]^T = \overline{f}_1\left({}^b\overline{x}_d, l_1,\ldots..,l_n\right) \quad (3)$$

cannot determine the actions of redundant manipulators, as there are an infinity of solutions that can achieve a given goal.

This has led to determining optimal paths whereby multiple solutions are revised with anticipation of finding a single path through cost benefit functions. In centrally controlled systems, this method results in redundancy largely complicating a system's controllability since singularities have to be bypassed for any given goal.

Advantages of central system control allow for total control of the manipulator and can also be viewed as action-based because the central processing unit calculates all required motion of each actuator prior to distributing this information.

2.2 Decentralized Method

The decentralized method enables each link to act independent of other links [Vittor *et al.*, 2004]. The method suggests the possibility of a modular approach of cloned links connected to achieve system controllability. It removes the central processing unit thereby removing the ability of any controller to co-ordinate the motion of all links. This leads to limited information storage. Information is not analyzed centrally to contribute to system actions. Motion is determined by multiple processors working independently to achieve a goal. Whereas the centralized method can be viewed as top-down, the decentralized is bottom-up.

Even though the links appear in series on the physical layout, they operate independently of each other, eliminating the central full reconstruction of the manipulator kinematics within one controller. Further, it removes the requirement of the central controller, as no reconstruction of information is required once distributed among the links.

The removal of the central processor coupled with the uni-directional data flow along the arm allows for modularization of the system, as all data can now be processed within the manipulator links. To achieve a bottom-up approach in a system, each module must view the goal from an unique perspective, utilizing the system's redundancy and goal data flow modified by each link. The desired angular motions can be found for each link,

$$\left[\theta_{x_i},\theta_{y_i}\right]^T = \overline{f}_2\left({}^i\overline{x}_{err}\right) \quad i = n, n-1, n-2\ldots \quad (4)$$

where

$${}^i\overline{x}_{err} = \overline{f}_3\left({}^i\overline{x}_e, {}^i\overline{x}_d\right) \qquad i = n-1, n-2\ldots \quad (5)$$

$${}^i\overline{x}_e = \overline{f}_4\left({}^{i+1}\overline{x}_e, \theta_{x_{i+1}}, \theta_{y_{i+1}}, l_i\right) \quad (6)$$

$${}^i\overline{x}_d = \overline{f}_5\left({}^{i+1}\overline{x}_d, \theta_{x_{i+1}}, \theta_{y_{i+1}}, l_i\right) \quad (7)$$

If each link has an embedded microprocessor, manipulator motion can be achieved through decentralized control, with links acting independently to achieve an overall goal.

A further characteristic of the method is the lack of a base reference in the system. This allows for the approach not to be limited by the number of links in the manipulator. Modules can be added or removed from the system without modification to system controllability.

3 Decentralized Manipulator Layout

A simulation in MATLAB Simulink was produced to demonstrate the practicality of decentralized control. Each link knows its own angular offsets, 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 is shown in Figure 3, where ${}^{b}\bar{x}_e$ is the end effecter position relative to base, ${}^{n}\bar{x}_e$ is the end effecter position relative to final link, ${}^{b}\bar{x}_d$ is the desired end effecter position relative to base and ${}^{n}\bar{x}_d$ is the desired end effecter position relative to final link. The information flow is limited 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, as shown in the link schematic in Figure 4.

The links are further composed of:

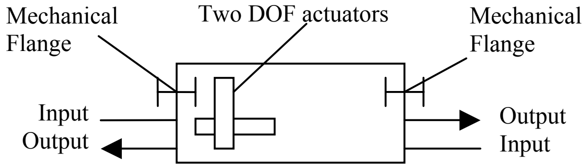

Figure 4. Link Schematic

- 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
- Power source and distribution

As two axes of rotation exist for each link, rotation occurs around the y-axis first following by rotation around the x-axis. For the example shown in this paper, six links are used by way of demonstration. In the simulation, an initial condition goal relative to the base ${}^{b}\bar{x}_d$ is constant.

where

$${}^{n}\bar{x}_e = {}_{0}^{1}\underline{T}^{-1}\,{}_{1}^{2}\underline{T}^{-1}\cdots{}_{n-2}^{n-1}\underline{T}^{-1}\,{}_{n-1}^{n}\underline{T}^{-1}\,{}^{b}\bar{x}_e \qquad (8)$$

$${}^{n}\bar{x}_d = {}_{0}^{1}\underline{T}^{-1}\,{}_{1}^{2}\underline{T}^{-1}\cdots{}_{n-2}^{n-1}\underline{T}^{-1}\,{}_{n-1}^{n}\underline{T}^{-1}\,{}^{b}\bar{x}_d \qquad (9)$$

The above equations are used to represent the stereo vision ${}^{n}\bar{x}_{err}$ data in the simulation.

$${}^{n}\bar{x}_{err} = \bar{f}_6\left({}^{n}\bar{x}_e, {}^{n}\bar{x}_d\right) \qquad (10)$$

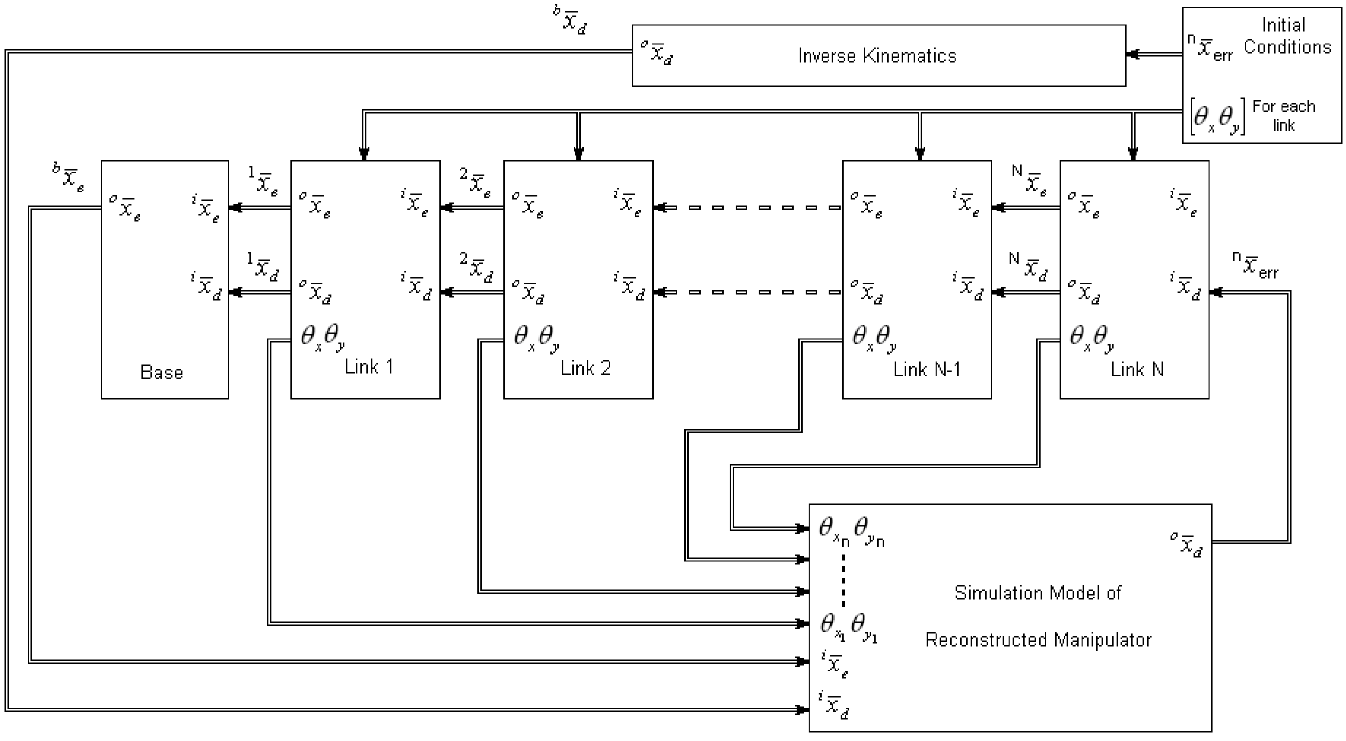

Figure 3. Data Flow in N-Link Manipulator Simulation

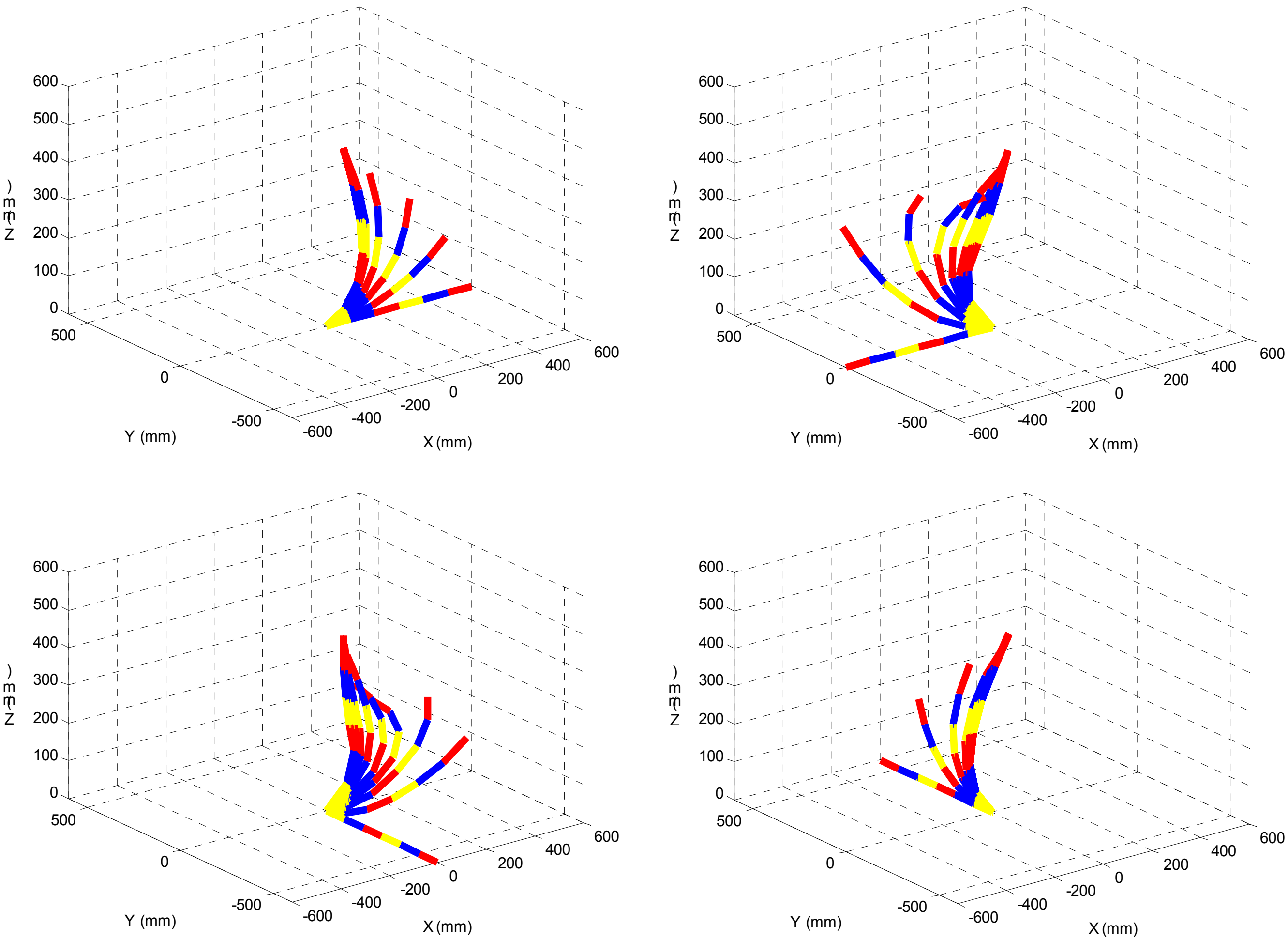

Figure 5. Varying Initial Condition Manipulator Paths

In the simulation the length of each link is assumed to be constant, resulting in 12 DOF motion, where each link's angles are known only to the link itself.

4 Results

Figure 5 shows the goal (300,300,350) can be reached by paths that look close to optimal, covering all the possible initial conditions in approaching the goal. In observing the path generated, the common goal is reached from four initial conditions in quadrant on the ground plane. Stable motion is observed in each of the links as well as the overall end effecter motion. The control method appears to be both versatile and robust. Singularities are avoided if the length of the deployed arm is greater than the distance to the goal. If not, then the arm can be shown to point directly at the goal and measure the shortfall in distance.

Attention was then turned to analyzing one particular manipulator motion with the end effecter initially at (-600,0,0) keeping the same goal. Motion of the end effecter relative to the base is shown in Figure 6(a) and is composite, disguising the motion of each link, demonstrating decentralized bottom-up control. In Figure 6(b), it can be noted that the end effecter appears to overshoot the observed goal in all three axes when approaching the goal. This, however, is not a true representation of the motion observed. Figure 6(a) shows that no overshoot exists during the final approach of the goal.

A further characteristic, as observed in Figure 6(b), is that the final approach by the end effecter to the goal is eventually limited to the z-axis in the reference frame of the end effecter. This is favorable in that one normally approaches an object in the z direction in order to manipulate it.

Figure 7 shows that there is proportionately more overshoot present in links when moving further from the base. This can be observed in both x and y actuators, though overshoot is more prominent around the y-axis. This is consistent with the transformation choice in the simulation where rotation occurs around the y-axis followed by the x-axis. Movement of the end effecter is larger for equal movements of actuators in going from the end effecter to the base, leading to more overcompensation as we move out from the base along the arm.

The error profiles in Figure 7, as observed by each link include not only the motion of the individual link, but also incorporate motion of the five other links. Figure 8 shows, that in attempting to reach the goal, there is a prominent directional change in the motion profile of links positioned further from the base. The overshoot in

Figure 7 can be clearly correlated with the relative link motion profiles. The changes in motor directions as observed in Figure 8 appear undesirable e.g. link 6 angles returning close to their original values. When viewing the overall motion in Figure 5 such motion is desirable in finding a smooth path to the goal.

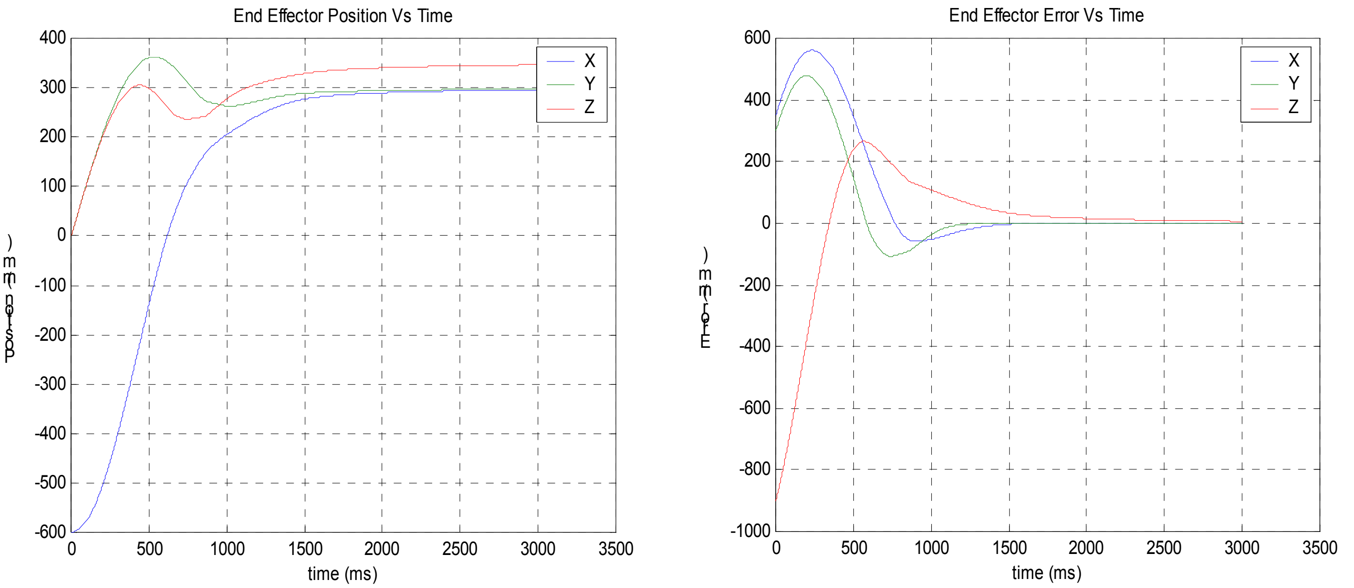

Figure 6. End Effecter (a) Position Relative to Base (b) Error

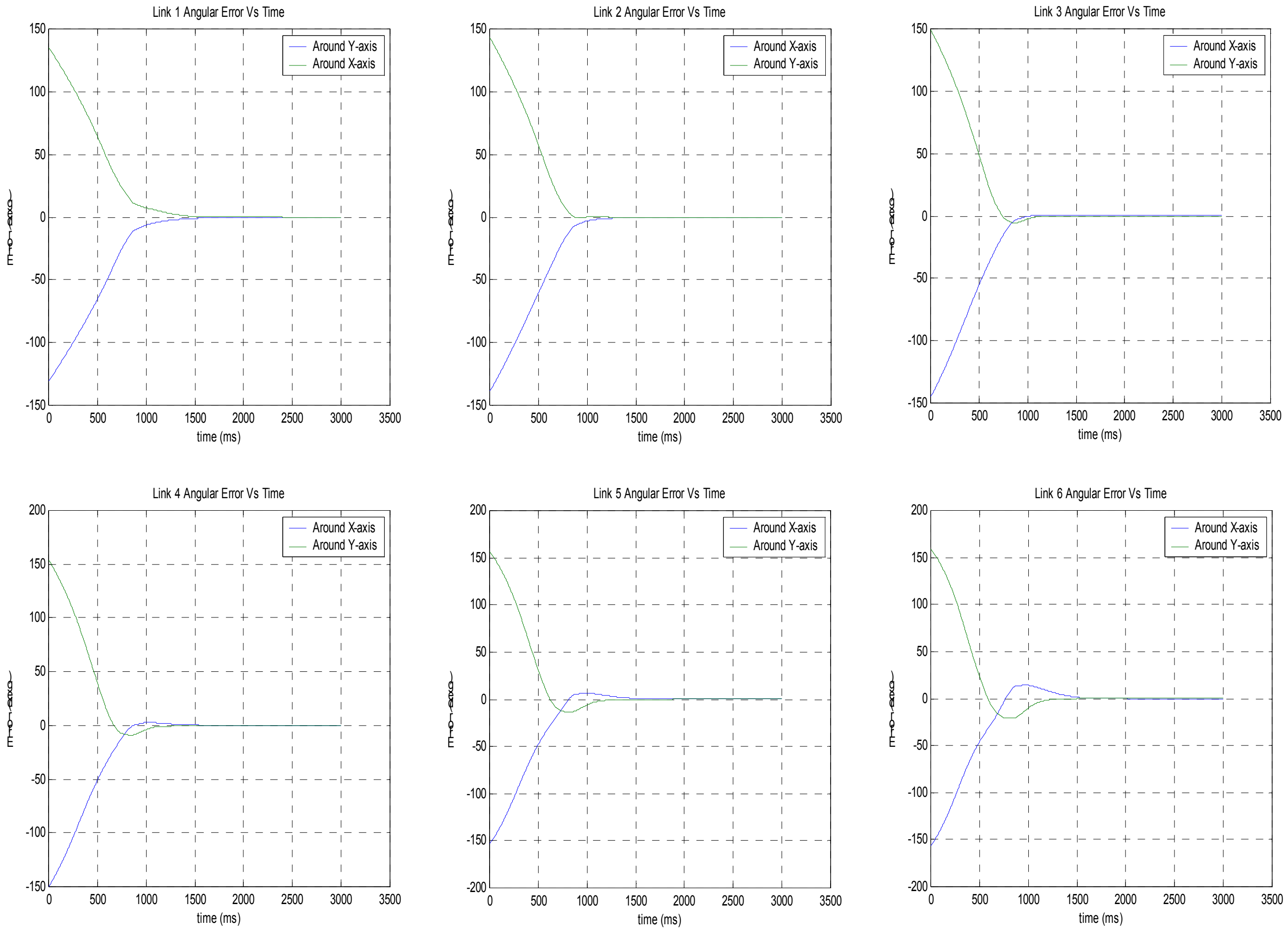

Figure 7. Relative Observed Link Error Profiles

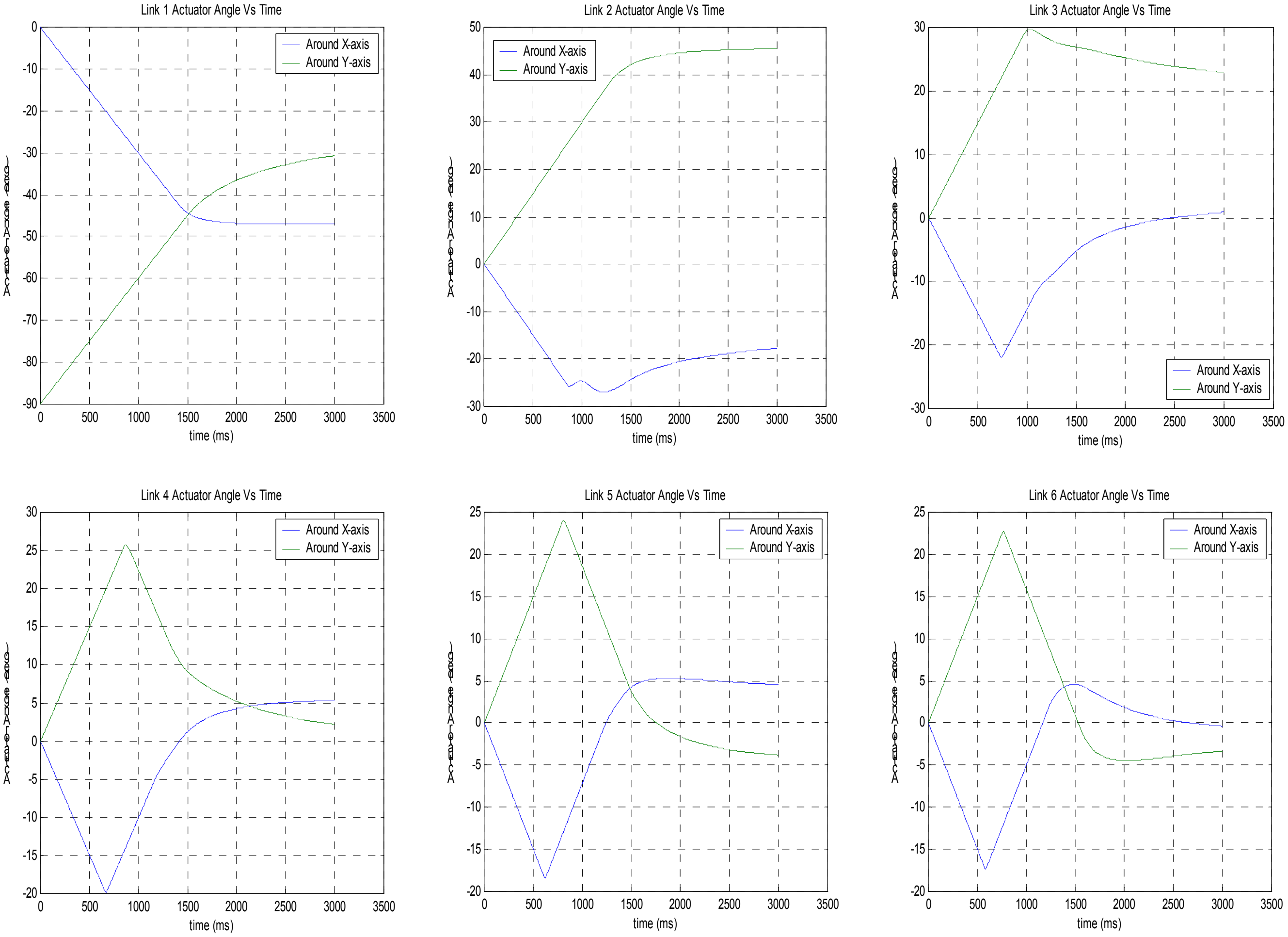

Figure 8. Link Actuator Motion Profiles

5 Fruit Picking Scenario

Having now created a situation in which control of an arm module can be localized, the basic decentralized control can be further enhanced by adding sensors to each module of the arm. This means that the sensors can feed information to the local microprocessor that will adjust the position of the module around obstacles. If the end effecter senses fruit within the canopy of the tree and attempts to reach the fruit, thereby bringing the arm into conflict with branches, the goal will still be approached even if some modules of the arm have to deflect from the position they would have adopted in the absence of the branches.

Another aspect of control in a fruit picking environment is the interference of viewing fruit by leaf matter. If leaves interrupt viewing fruit, it is possible within a limited context to maintain an attempt to reach the goal in the absence of definitive information from the stereo vision. As long as the interruption is temporary then motion towards the goal can continue until stereo vision identifies the fruit again.

6 Conclusion

This paper has demonstrated a decentralized controller for a six link 12 DOF modular manipulator system. Simulation results show a smooth path end effecter motion profile while allowing for manipulator obstacle avoidance. The decentralized control method appears to be both versatile and robust, utilizing the flexibility and redundancy of the complete manipulator.

The advantages of the decentralized control method include:

- There is no need for a complete system model.
- Full environment reconstruction in one master controller is bypassed by having localized sub-goals for each module.
- Decentralized control of the arm assists modular construction and selecting among the hyper-redundancy infinity of solutions.
- Computational burden is kept down by restricting inverse kinematics to within each module.
- Local environment conditions can influence control.

7 Future Work

For the system demonstrated in this paper, time constants on each module were the same. To further improve the approach characteristics of the end effecter to the goal, changing these time constants in some optimal way will be considered.

Much scope exists for future work in the optimization of decentralized control theory, as much in automated fruit picking application as in the broad field of redundant system control.

Work is currently being undertaken to construct a physical system with which to demonstrate the practical application of decentralized control theory in fruit picking.

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