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# Dual Arm Robotic System With Sensory Input

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**1. Abstract**

The need for dual arm robots in space station assembly and satellite maintainance is of increasing significance. Such robots will be in greater demand in the future when numerous tasks will be assigned to them to relieve the direct intervention of humans in space. Technological demands from these robots will be high. They will be expected to perform high speed tasks with a certain degree of autonomy. Various levels of sensing will have to be used in a sophisticated control scheme.

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## 2. Introduction

The need for dual arm robots in space station assembly and satellite maintainance is of increasing significance. Such robots will be in greater demand in the future when numerous tasks will be assigned to them to relieve the direct intervention of humans in space. Technological demands from these robots will be high. They will be expected to perform high speed tasks with a certain degree of autonomy. Various levels of sensing will have to be used in a sophisticated control scheme.

In this presentation we will briefly describe ongoing research in control, sensing and real-time software to produce a two-arm robotic system that can accomplish generic assembly tasks. The paper will concentrate mostly on the control hierarchy, the specific control approach selected being the Variable Structure (Sliding Mode) Control approach. We will consider a decentralized implementation of model-reference adaptive control using Variable Structure controllers and the incorporation of tactile feedback into it.

We assume that multi-arm robotic operations have a hierarchical/decentralized control structure. However, the appropriate control algorithms have to be chosen for feedback to properly fit the special hierarchy of multiple robots with dextrous end effectors. A specific control approach has to be selected, and its requirements can be clearly specified:

- It must easily decompose into a hierarchy.
- It must be ameanable for modular implementation.
- It must posess low real-time computation requirements.
- It must be able to receive changes from sensor data.
- It must be insensitive to modeling errors and load variations.

It is expected that robotic systems will become an important part of future space missions. Orbital Maneuvering Vehicles have been proposed with dual arm systems for space station assembly, satellite servicing, etc.. Although the importance of dual arm robotic systems have been recognized for some time, little work of a general nature has been done in controlling such systems.

Early multi-processor robotic controllers were based on the principle of a simpler low-level processor and a more sophisticated high-level computer. This made interfacing fairly difficult and expansion almost impossible. With today's processors and appropriate software load distribution, tasks at all levels can be handled by processors of the same family. Coordination of data transfers are extremely simplified. It is apparent that certain improvements will have to be made over conventional control structures (as used say, in the PUMA) if there is hope of accomplishing sophisticated assembly type operations using multiple manipulators. For versatile performance the control hierarchy will exhibit a finer task decomposition. Tasks will have to be relegated to a large number of processors. Sensory inputs will have to be appropriately assigned.

The control of robots in a precise, reliable and repeatable manner is by itself a hard problem. The problem becomes somewhat more complicated when considering the control of coordinated robot arms. Limited work has been done in the area of multi-arm robot systems [1] [2], [3], [4], [5], [6] and [7].

A method developed for controlling manipulator arms by Young [8], Özgüner and co workers [9], [10], and others [11] utilising variable structure control theory is particularly ameanable to extension to multiple arm systems controlled within a hierarchical framework. Initial work along these lines have already been performed. In this paper we will be reporting on recent developments in the above approach and especially tactile sensing feedback from the end effector as included in the hierarchical control structure.

There appear to be certain generic tasks that are imbedded in many assembly and maintainance operations. These include:

- Pick and place type tasks.
- Pin in the hole type tasks.
- Combined rotation-translation type tasks.

Many complex operations can be partitioned into combinations of these generic tasks. Thus the control algorithm design and related software will concentrate on the above tasks.

Figure 1 summarizes the control hierarchy to be used. At Level I, parsing interpreting and decoding user commands and high level sensory input are accomplished. Error messages to the user are also generated at this level. Level II includes trajectory planning, associated coordinate system transforms and analysis of bounds of the workspace. Joint-level coordination and transfer of information required by control algorithms is carried out at Level III. At Level IV, generation of the feedback control and I/O with actuators and force sensing is accomplished. The control algorithm selected has to be strongly coupled to the information structure selected. The algorithm must be decomposable into the hierarchy imposed and inherently adaptive to load and trajectory variations. The algorithm/control approach we are utilizing is the *Decentralized Model Reference* Adaptive approach using Variable Structure (sliding mode) controllers. It appears that this algorithm with appropriate modifications to accomodate sensory input and user commands can be mapped onto a multiprocessor system.

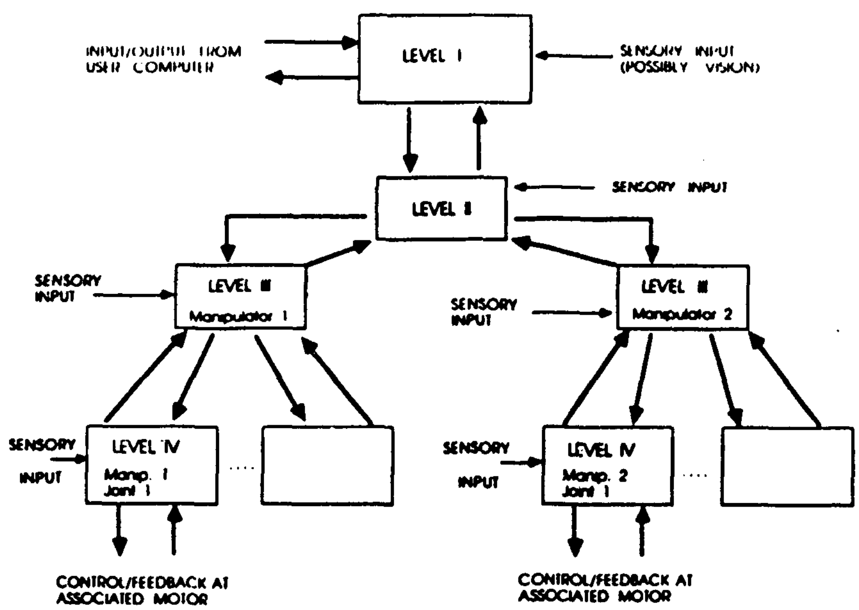


Figure 1: The General Hierarchy for the Control of Two Manipulators

Various results have been recently reported in the utilisation of sensory information from the end-effector in the feedback control structure. In the present work we will be using the force feedback approach (tactile sensing) as reported in [12]. The incorporation of force feedback into the control algorithm is not straight-forward, and in the next section we will introduce the concept of *interaction compensation* which will aid in the analysis.

## 3. The Concept of Interaction Compensation

It has been previously claimed that the levels of a hierarchy (as in the multi-manipulator system of Figure 1), can be classified so that one identifies "increasing intelligence with decreasing precision", as one moves up [13]. As with most labeling schemes, this may be an over-generalisation and there may be numerous cases where proper *relegation* of (a) Control Authority, and (b) Information Distribution, may result in preferrable operation of the over-all system.

We will consider the regulation of an interconnected system to introduce the concept of Interaction Compensation, which we will subsequently apply to the specific case of multi-manipulator control; under a fixed Control Authority structure and control algorithm.,

Consider a large-scale system consisting of $N$ interconnected subsystems each defined by

$$\dot{x}_i = A_i(x_i)x_i + B_i(x_i)u_i + E_i(x) \quad (1)$$

$$y_i = D_i x_i \quad , \quad (2)$$

for $i = 1, 2, \ldots, N$, where $x_i \in \Re^{n_i}$, $u_i \in \Re^1$, $y_i \in \Re^1$, where $\Re$ represents the real Euclidean vector space, $x^T = (x_1^T, x_2^T, \ldots, x_N^T)$ and the matrices are of compatible dimension. $E_i(x)$ denotes the totality of interaction effects from the remaining subsystems to subsystem $i$. Note that $E_i(x)$ may also include modeling errors.

Let us first define what is meant by *insensitivity to interaction*. Consider again (1)-(2), rewritten for brevity as

$$\dot{x}_i = f(x_i, u_i) + \Delta(x, t) \quad , \quad (3)$$

for the state transition mapping $f : \Re^{n_i} \times \Re \longrightarrow \Re^{n_i}$ and the total interaction term $\Delta(x, t)$. The system (3) is said to be *insensitive* to interaction effects if the solution $x_i(t)$ may be expressed as

$$x_i(t) = \bar{x}_i(t) + O(\epsilon_i) \quad ,$$

where $\bar{x}_i(t)$ solves $\dot{x}_i = f(x_i, u_i)$, for all $\epsilon_i > 0$ and all $t > T$, for some finite time $T$, and $O(\epsilon_i)$ represents terms of degree two or higher in $\epsilon_i$.

In reference to measurements available for use at the control inputs of subsystem $i$ we can now consider three possibilities:

1. Full (real-time) interaction information.
2. Partial interaction information.
3. Interaction modeling.

It can be shown that interaction information provides the opportunity of directly negating all effects within the range space of $B_i$. The more interesting cases are when partial information is available or can be *generated* through dynamic modeling of the interactions.

Given the model, the decentralized control problem is to design a controller to feedback locally available real-time information such that the states of each local subsystem are regulated to zero or track the states of a local reference model.

Let the local reference model for the $i$-th subsystem be given as

$$\dot{\hat{x}}_i = \hat{A}_i \hat{x}_i + \hat{B}_i r_i \quad (4)$$

$$\hat{y}_i = \hat{x}_i \quad , \quad (5)$$

with $\hat{x}_i \in \Re^{n_i}$, $\hat{A}_i \in \Re^{n_i \times n_i}$, $\hat{B}_i \in \Re^{n_i \times 1}$, where $r_i$ is a scalar reference input. Define the *local* error between the $i$th subsystem and its local reference model in the manner

$$e_i = \hat{x}_i - x_i \quad (6)$$

so that the local error system dynamics may be written in the form

$$\dot{e}_i = \hat{A}_i e_i + (\hat{A}_i - A_i)x_i + \hat{B}_i r_i - B_i u_i - E_i(x) \quad . \quad (7)$$

Within this framework, assume that

- **Each local controller design is dependent only on the local model.**
- **The systems (1)-(2) and (4)-(5) are controllable.**
- **The states $x_i$ and $\hat{x}_i$ are measureable locally for feedback to the $i$th input.**
- **Reference trajectory information may be fed to a subsystem from a higher level coordinator but interaction information is only partially available in real-time, and the subsystem is not allowed to communicate with the other local controllers**

### 4. Variable Structure Controllers

In this presentation we are going to assume that the basics of Variable Structure Control are known. An important feature of Variable Structure Controllers is the fact that, for the decentralised case, the local subsystem is made insensitive not only to local parameter changes but also to dynamical interactions with neighboring subsystems once the sliding surface is reached.

We define the sliding surface corresponding to the system (1)-(2) as

$$\sigma_i = C_i e_i \quad , \tag{8}$$

for $C_i$ in $\Re^{1\times n_i}$. Invariance properties of the sliding surface were given in [14,15]. Refering back now to the error system (7), the control law is formulated in the manner

$$u_i = K_{e_i} e_i + K_{x_i} x_i + K_{r_i} r_i + \delta_i \quad , \tag{9}$$

where $K_{r_i}$ in $\Re^1$, $K_{x_i}$ in $\Re^{1\times n_i}$, and $K_{e_i}$ in $\Re^{1\times n_i}$ can be specified in different regions of the state space, and where $\delta_i$ is usually a constant picked according to the norm of the interactions. The elements $K_{r_i}$, $K_{x_i}$, $K_{e_i}$, and $\delta_i$ are discontinuous functions of the sliding surface and the coefficients of system and reference model state equations. We furthermore claim that estimates for $\delta_i$ can be refined with knowledge on interactions. In the following we derive the appropriate forms based on the reaching condition which, in view of (7), (8) and (9), becomes

$$\begin{aligned} \sigma_i \dot{\sigma}_i &= C_i[\hat{A}_i - B_i K_{e_i}] e_i \sigma_i + C_i\{[\hat{A}_i - A_i] - B_i K_{x_i}\} x_i \sigma_i \\ &+ C_i[\hat{B}_i - K_{r_i} B_i] r_i \sigma_i - C_i\{B_i \delta_i + E_i(x)\}\sigma_i \\ &< 0 \end{aligned} \tag{10}$$

The condition (10) is satisfied provided that the gain parameters and $\delta_i$ are chosen so as to make each term negative. Thus,

$$(K_{e_i})_\ell = \alpha_{i\ell}(C_i B_i)^{-1} \left\{ \sum_{j=1}^{n_i} c_j^i \hat{a}_{j\ell}^i \right\} \mathrm{sgn}[(e_i)_\ell \sigma_i] \quad ; \tag{11}$$

$$(K_{x_i})_\ell = \beta_{i\ell}(C_i B_i)^{-1} \left\{ \sum_{j=1}^{n_i} c_j^i (\hat{a}_{j\ell}^i - a_{k\ell}^i) \right\} \mathrm{sgn}[(x_i)_\ell \sigma_i] \quad ; \tag{12}$$

$$K_{r_i} = \left\{ \gamma_i (C_i B_i)^{-1} C_i \hat{B}_i \right\} \mathrm{sgn}[r_i \sigma_i] \quad ; \tag{13}$$

where $\alpha_{i\ell}$, $\beta_{i\ell}$, $\gamma_i$ are positive constants, and $(\,\cdot\,)_\ell$ represents the $\ell$th element of the indicated vector. Let

$$\Delta_i = \max \; \| E(x) \| \quad , \tag{14}$$

and assuming that the *only* locally available information is $\Delta_i$, we can pick

$$\delta_i = \Delta_i (C_i B_i)^{-1} \; \| C_i \| \; \mathrm{sgn}[\sigma_i] \quad , \tag{15}$$

On the other hand, if the interaction effects are split into two portions; namely an unknown (but with known bound) portion, and a measurable portion, as given below:

$$E_i(x) = E_{iu}(x) + E_{im}(x) \quad , \tag{16}$$

the concept of *interaction compensation* can be utilised to directly negate the effects of the measured portion. Furthermore, if for specific applications, the measurable interactions are to assume desired values, or follow prespecified trajectories in time, they can be included easily into the model-reference framework above.

## 5. Robotic System Configuration and Modeling

The system under consideration consists of two different robotic arms, each a planar three-link manipulator (Figure 2). The parameters of each link are shown in the figure where

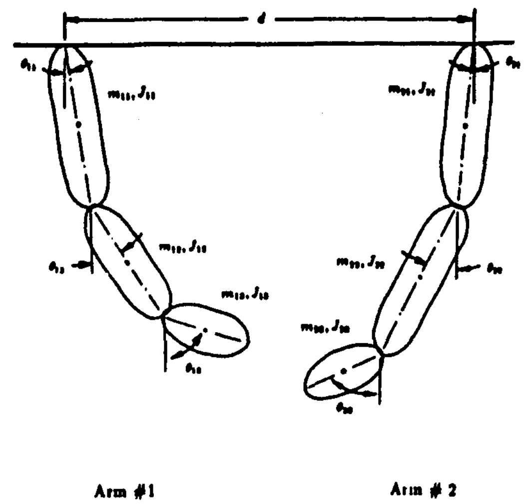


Figure 2: Two three-link, planar manipulators.

| | | |
|---|---|---|
| $L_{ij}$ | $\triangleq$ | Length of each link $\quad i = 1,2;\ j = 1,2,3$ |
| $\ell_{ij}$ | $\triangleq$ | Location of center of gravity with respect to the end of the previous link |
| $m_{ij}$ | $\triangleq$ | Mass of $ij$-th link |
| $J_{ij}$ | $\triangleq$ | Moment of inertia about the corresponding center of gravity |
| $\theta_{ij}$ | $\triangleq$ | Angular position measured counterclockwise |
| $T_{ij}$ | $\triangleq$ | Torque actuating the $ij$-th joint |
| $d$ | $\triangleq$ | Distance separating both arms (on the base) |

The overall task can be divided into three phases: approaching phase, grasping phase, and lifting (coordination) phase. In the approaching phase each arm moves toward the object to be picked. Speed and position control are applied according to the characteristics of each arm. The grasping phase design, although not considered in our study, depends on the sensory system assumed to be available. Force sensing can be utilised to implement a controller using force feedback. The last phase is the lifting phase during which the two-arm robotic system forms a closed-chain mechanical manipulator. Again, tactile feedback can be applied at this phase and we will discuss incorporation of such *interaction information* below. Lagrange's method has been used in finding the dynamical equations of this robotic system, where the equations are written in terms of the total kinetic energy ($K$) of the system, the total potential energy ($P$) of the system, and a set of independent coordinates ($q_i$) chosen to describe the configuration of the system. Furthermore, these equations may include dissipation functions for non-conservative systems. We will not present these equations here but just briefly analyze the conditions while the two arms are in contact. For the first arm, let

$$
\begin{aligned}
\theta_1 &= (\theta_{11}\ \theta_{12}\ \theta_{13})^t \\
T_1 &= (T_{11}\ T_{12}\ T_{13})^t \quad , \qquad (17)
\end{aligned}
$$

It can then be shown that, in the approaching phase the dynamical equations of the first arm can be written as

$$M_1\ddot{\theta}_1 + F_1(\theta_1, \dot{\theta}_1)\dot{\theta}_1^2 + G_1\theta_1 = T_1 \quad , \tag{18}$$

where $\dot{\theta}_1^2 = (\dot{\theta}_{11}^2, \dot{\theta}_{12}^2, \dot{\theta}_{13}^2)^t$.

On the other hand, during the grasping and holding phases, a closed chain robot is formed through the continuous contact of the end effectors of both arms with the object. This constraint defines a frictionless manifold which can be expressed in closed form. It is assumed that an additional torque (to be denoted as $\tau_1$) can be defined to maintain the tip of the end effector on the manifold. The dynamical equations of the closed chain may then be written as

$$M_1\ddot{\theta}_1 + F_1(\theta, \dot{\theta}_1)\dot{\theta}_1^2 + G_1\theta_1 = T_1 + \tau_1 \quad . \tag{19}$$

To find the equation for $\tau_1$, consider a vertical displacement ($\delta s$). The corresponding work done by $\tau_1$ is zero; that is,

$$\begin{aligned} \delta W &= \tau_1 \delta s \\ &= -F_{14}^x \delta x + F_{14}^y \delta y \quad , \end{aligned} \tag{20}$$

where $F_{14}$ is a generalized force due to the contact. The above equation can then be expressed in terms of the joint angles since

$$\begin{aligned} x &= L_{11}\sin\theta_{11} + L_{12}\sin\theta_{12} + L_{13}\sin\theta_{13} \\ y &= -L_{11}\cos\theta_{11} - L_{12}\cos\theta_{12} - L_{13}\cos\theta_{13} \\ \delta x &= L_{11}\cos\theta_{11}\delta\theta_{11} + L_{12}\cos\theta_{12}\delta\theta_{12} + L_{13}\cos\theta_{13}\delta\theta_{13} \\ \delta y &= L_{11}\sin\theta_{11}\delta\theta_{11} + L_{12}\sin\theta_{12}\delta\theta_{12} + L_{13}\sin\theta_{13}\delta\theta_{13} \quad . \end{aligned}$$

Substituting the above into (20) results in

$$\tau_1 = \frac{\delta\omega}{\delta\theta} = \begin{bmatrix} (F_{14}^x\cos\theta_{11} + F_{14}^y\sin\theta_{11})\,L_{11} \\ (F_{14}^x\cos\theta_{12} + F_{14}^y\sin\theta_{12})\,L_{12} \\ (F_{14}^x\cos\theta_{13} + F_{14}^y\sin\theta_{13})\,L_{13} \end{bmatrix} = \begin{bmatrix} \tau_{11} \\ \tau_{12} \\ \tau_{13} \end{bmatrix} \quad . \tag{21}$$

Furthermore, since $F_{14}^x$ and $F_{14}^y$ are along the direction of motion and normal to it, they are related by $F_{14}^y = \mu F_{14}^x$ where $\mu \leq 1$ is the coefficient of friction.

Following the same procedure used for deriving the equation of the first arm, one can easily find the dynamical equations of the second arm. Furthermore, a similar equation to (21) can be found for the second arm to satisfy the coordination movement constraint. The decentralized model-reference adaptive controller is now utilised to control the robotic system. To this end, each link is considered an independent subsystem with coupling forces and/or torques being the interactions. Thus,

$$\begin{aligned} S_1 &\triangleq \text{Link \#1 of the first arm with } X_1 = (x_{11}\ x_{12})^t = (\theta_{11}\ \dot{\theta}_{11})^t \\ S_2 &\triangleq \text{Link \#2 of the first arm with } X_2 = (x_{21}\ x_{22})^t = (\theta_{12}\ \dot{\theta}_{12})^t \\ S_3 &\triangleq \text{Link \#3 of the first arm with } X_3 = (x_{31}\ x_{32})^t = (\theta_{13}\ \dot{\theta}_{13})^t \\ S_4 &\triangleq \text{Link \#1 of the second arm with } X_4 = (x_{41}\ x_{42})^t = (\theta_{21}\ \dot{\theta}_{21})^t \\ S_5 &\triangleq \text{Link \#2 of the second arm with } X_5 = (x_{51}\ x_{52})^t = (\theta_{22}\ \dot{\theta}_{22})^t \\ S_6 &\triangleq \text{Link \#3 of the second arm with } X_6 = (x_{61}\ x_{62})^t = (\theta_{23}\ \dot{\theta}_{23})^t \quad . \end{aligned}$$

Each subsystem of the above has the following general form:

$$\dot{X}_i = A_i(X_i, t)X_i + B_iU_i + \sum_{\substack{j=1 \\ j\neq i}}^{6} A_{ij}(X, t)X_j \quad , \tag{22}$$

where $U_i = T_i$. Detailed derivations of these equations in the above form may be found elsewhere [16]. One can note that any measured torque or force betwean the links can be incorporated into the control structure discussed previously.

## 6. Controller Design

The use of Variable Structure Controllers for robotic system control was introduced by Young [8]. Among more recent work in the area one can cite those of Morgan and Özgüner [9] where *decentralized* controllers were employed, of Slotine and Sastry [11] who dwell on the reduction of chattering, and of Young [14] who introduces the design of variable structure model-following control systems. The present work differs from the above in that it uses a Decentralized, Model Reference Adaptive approach and specifically addresses the multiple manipulator control problem. The controller devised for this robotic system is organized in a hierarchical framework. The levels of the hierarchy are divided into two, and the information processed at each level is not directly available to the other level. Figure 3 shows the levels and information flow of the hierarchy, indicating that there are two paths of information flow. Downward moving data presents the flow of commands while upward moving data presents the flow of feedback information. As shown in Figure 4, three tasks are defined at upper level: planning the motion of the end effectors of both arms, defining the local reference inputs for each link, and finding the upper bound of the dynamical interactions between subsystems. Figure 4 schematically depicts the operations done at this level.

The end effectors of both arms are required to move in the work-space in a specific way. A path is a continuous curve in the system workspace connecting the tip initial configuration to the final configuration through all intermediate configurations. On the other hand, a trajectory is a continuous curve in the state space of every link joining the initial state to the final state. In other words, the trajectory contains all the information about the time history of position, velocity, and acceleration for each link. Therefore, a trajectory includes not only a path but also velocity and acceleration at every point at the path.

The first step in generating the two arm robot motion is to characterise the path in some manner, typically by applying physical intuition to some extent. Esentially, the arm should start and stop slowly with a smooth motion. A number of different trajectories may be proposed to satisfy the requirements, such as exponential and polynomial trajectories.

In the present study, the following equations were used

$$x(t) = x(t_f) + [x(t_o) - x(t_f)]e^{-a(t-t_o)^n} \quad (23)$$

$$y(t) = y(t_f) + [y(t_o) - y(t_f)]e^{-b(t-t_o)^m} \quad , \quad (24)$$

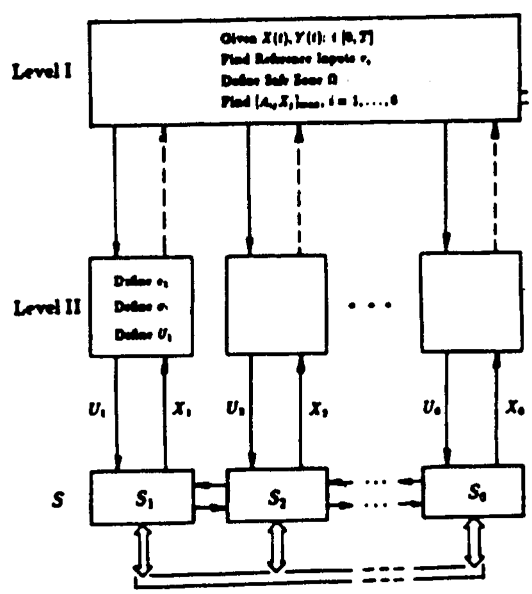


Figure 3: Control Hierarchy

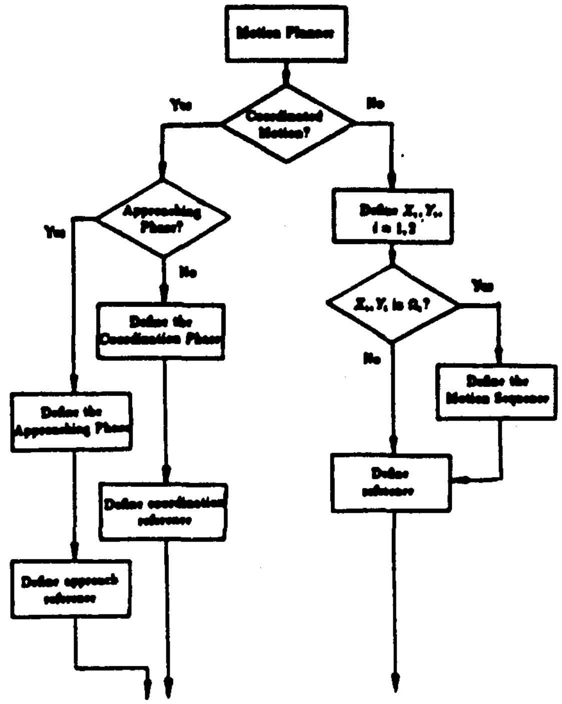


Figure 4: High Level Controller

where $a, b, m$, and $n$ are real numbers. In finding the reference input $r_i$ for every link of each arm, the inverse dynamics approach is utilized. Note that, in the coordination (actual lifting) phase, both end effectors move on the same path. During this phase, if a desired contact force profile is required, this can also be cast in the framework of reference generation in the given formulation.

The low level controller consists of individual controllers for each link. Each controller is designed following the model reference adaptive, variable structure system approach. In this level, each subsystem is controlled separately to follow the reference model. This is to be done using only local information such as position and speed information of both the subsystem and the corresponding local reference model. Furthermore, the local controller required to force the local states to follow the states of the corresponding reference model is designed using the VSS approach presented earlier. Further details and simulation studies of cases without tactile feedback may be found in Ref. [16].

## 7. Conclusion

In this presentation we have briefly described ongoing research in control, sensing and real-time software to produce a two-arm robotic system that can accomplish generic assembly tasks. We have concentrated mostly on the control hierarchy, the specific control approach selected being the Variable Structure (Sliding Mode) Control approach. The decentralised implementation of model-reference adaptive control using Variable Structure controllers was shown to be particularly suitable for such an application and the incorporation of tactile feedback was possible. Research is presently continuing on adjustments in the feedback gains when a desired torque/force profile is given for end-effectors in contact with each other or other external surfaces.

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