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ANALYSIS OF COOPERATIVE ROBOTS

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Abstract: *This paper presents the analysis of control of cooperative robots utilizing structural flexibility in gripper design to avoid large unwanted internal forces acting on multi-robot systems. The paper also deals with estimation of characteristics of robots analyzing arm joint accuracy, arm joint load and arm joint utilization.*

Key words: *cooperative robots, compliant grippers, control of forces, control of moments, multi-robot system*

1. INTRODUCTION

Multiple cooperating robots make manufacturing systems more flexible and dexterous by allowing the systems to handle complex tasks that are beyond the capacity of a single robot. Multiple robots can be used in flexible automation work cells with one or more manipulator working as flexible fixtures, thereby minimizing rigidity of the work cell and also decreasing the time required for assembly. Multiple robots can be used to extend the work space of the system.

Coordinated controls of multi-robot systems have received considerable attention in the past years. Exist three kinds of coordination schemes in the literature. In the master-slave scheme one robot arm is under position control and the others are subject to compliant force control to maintain the kinematics constraint. The master-slave scheme has the advantage that each robot has an independent controller. The second scheme utilizes a centralized control architecture in which robots and the payload are considered as a closed kinematics chain, based on a unified robot and payload dynamic model. Most of the methods developed for the two arms grasping a common bad deal with control of only the relative position of end-effectors of the two manipulators. Complete analyses of the problem most include several other factors such as load sharing, control of interactive force/torque and internal forces and redundancy of actuation. The third scheme is a decentralized control in which each robot is controlled separately by its own local controller. Compared with the master-slave scheme there is no communication delay amongst robots. Compared with the centralized scheme the third is easy to implement with the decentralized scheme, sensors are usually used to measure interactions amongst robots.

Position is on the most usual variable to be controlled. Position control, including a control of velocity and acceleration can prove to be relatively inefficient. In position control, if is likely that certain amount of position error may be present at the end-effectors of the robot. When multiple robots grasp an object, under position control any misalignment or positional errors could yield undesirable forces existed on the robot. Moreover, the forces acting on the object can cause some damage to the object itself. Similarity, a purely force control is likely to lead to errors in position since there would be no position feedback, thus rendering this method unsuitable for many robots applications. Hence in cooperative robots applications it is preferable that the control scheme includes elements of both position and force control.

Another way is the use of structural flexibility in multi-robot system i.e. utilizing grippers with built-in compliance. This is one of the most simple and effective solutions to avoid excessive internal forces that are with the independent robot control.

2. INFORMATION

The compliant gripper consists of a rigid work piece fixed at the end of the robot and a flexible mechanism that is modeled as a spring system (Fig.1) [1, 6].

The spring used in the compliant gripper must be carefully selected. If the spring is too “hard” namely the stiffness is very high, the compliant gripper does not deform in response to robot trajectory errors, presenting possible damage from large internal forces.

If the spring is too “soft” namely the stiffness is very small, the largest allowable force produced by the “soft” spring may not be high enough to compensate for the

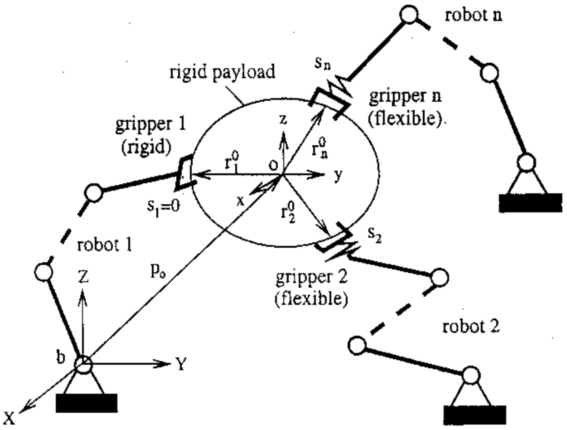

Fig. 1. Multiple robots manipulating a rigid payload. via flexible grippers.

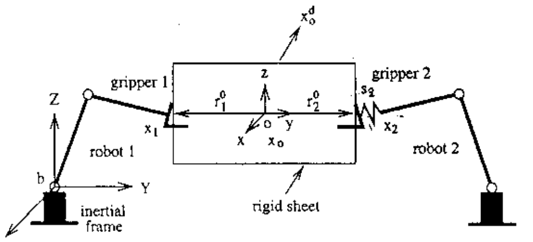

Fig. 2. A two-robot system manipulating a flexible sheet.

internal force generated by the maximum position errors of robots. In addition, a spring that is too “soft” may lead to serious vibrations.

The investigation is based on the clamped tree model where one gripper is rigid and the other flexible (Fig.2) [2], so that the payload motion and spring deformations can be uniquely determined. In some cases, the grippers may be flexible only along the specific directions in which potentially large geometric errors may occur due to first, task geometry uncertainty and second, tracking errors in position/orientation.

The kinetic energy of the payload-spring system is:

$$T = \frac{1}{2}\dot{x}^T \cdot H_p(x_0)\cdot \dot{x}_0 + \frac{1}{2}\sum_{i=2}^{n} m_{si} \cdot \dot{p}_i^T \cdot \dot{p}_i , \qquad (1)$$

where $H_p(x_0)$ denotes the inertia matrix of the payload and m_{si} denotes the mass of springs in gripper i ($m_{si} = 0$), p_i is the position vector $p_i \in R^{3\times 1}$ is represented by:

$$p_i = p_0 + R_b^0(\theta)\cdot r_i = p_0 + R_b^0(\theta)\cdot\left(r_i^0 + s_i\right), \qquad (2)$$

where $p_0 \in R^{3\times 1}$ is a position vector of the mass center of the rigid payload, $R_b^0(\theta) \in R^{3\times 3}$ denotes the rotation matrix of the frame $0 - xyz$ relative to the inertial frame $b - XYZ$, $r_i^0 \in R^{3\times 1}$ denotes a position vector of contact i which is constant and presented in the frame $0 - xyz$ and $s_i \in R^{3\times 1}$, represents the springs deformation of gripper i.

Substituting equation (2) in equation (1) we obtain:

$$T = \frac{1}{2}\dot{x}_o^T \cdot H_0(x_0,s)\cdot \dot{x}_0 + \frac{1}{2}\dot{s}^T \cdot H_s \cdot \dot{s} + \dot{x}_0^T \cdot W(\theta,s)\cdot \dot{s} . \quad (3)$$

The potential energy due to spring deformation is:

$$U_s = \sum_{i=2}^{n} s_i^T \cdot k_s \cdot s_i = \frac{1}{2} s^T \cdot k_s \cdot s , \qquad (4)$$

where $k_s = diag\{k_s\}$ denotes the stiffness matrix of the spring.

Applying Lagrange’s equation we obtain the dynamic equation of motion of the payload spring system consisting of the rigid payload dynamics.

$$H_0(\theta,s)\ddot{x}_0 + W(\theta,s)\ddot{s} + C_0(x_0,\dot{x}_0,s,\dot{s})\dot{x}_0 + G_0 = \sum_{i=1}^{n} R_{0i}^T(\theta,s_i) f_i \ ,\cdot (5)$$

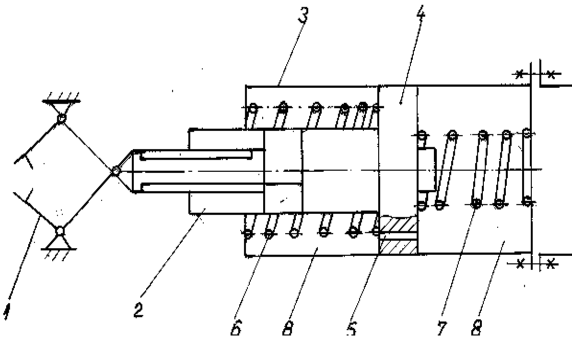

Fig. 3. Compliant gripper (University POLITEHNICA of Bucharest).

where G_0 is the gravitational force of the payload and the vibration dynamics.

$$W^T(\theta,s)\cdot \ddot{x}_0 + H_s \cdot \ddot{s} + C_s(x_0,\dot{x}_0,s)\cdot \dot{x}_0 + k_s \cdot s = -R_s^T(\theta,s)\cdot f \ , (6)$$

where $C_0(x_0,\dot{x}_0,s,\dot{s})$ and $C_s(x_0,\dot{x}_0,s)$ denote the complex nonlinear terms, $f = \left[f_1^T,\dots,f_n^T\right]^T$ and $R_s^T(\theta,s) \in R^{3n\times 6n}$.

The dynamic equation of motion of the complete system is given by:

$$D(x)\cdot \ddot{x} + C(x,\dot{x})\cdot \dot{x} + K \cdot x + G(x) = u + J^T(x)\cdot f \ . (7)$$

In the case when compliant grippers are not flexible in all coordinate directions, a force feed-forward control can be added to the PD scheme to control internal forces between robots and the payload in the coordinate directions without built-in compliance of grippers.

Another solution it is the author proposal for utilized a gripper with hydraulically buffer (Fig.3). This are composed from the end effectors 1, actuated of the hydraulic cylinder 2, placed in rod of hydraulically buffer 3, attach of the arm 4 of the robot. In piston 4, of the hydraulically buffer it is made a calibrated orifice 5. Springs 6and 7 are dimensioned such that in undid position of the gripper, piston 4 of the hydraulically buffer to be in median line position.

3. CONTROL OF FORCES AND MOMENTS

Control and coordination of multiple robots have made possible with the use of multiple sensory devices. Sensors play a dominant role in achieving this autonomous and intelligent behavior by allowing a system to learn about the state of its physical environment, and thereby interacting with is environment.

The methods used to fuse data from multiple sensors can be categorized along two types of approaches: Statistical Approach (Baysian Approach, Dempster Shafer Evidence Theory and Kalman Filtering) and Information Theoretic Approach (Expert Systems, Rule Based Systems and Adaptive Learning).

A Kalman Filter is an optimal recursive data processing algorithm that is based upon state space concepts. The variable estimated using Kalman Filter can be shown to be statistically optimal because it uses:

- Knowledge of system and measurement device dynamics;
- The statistical description of system noise, measurement errors, and uncertainty in dynamics models;
- Any available information about the initial conditions of variables of interest.

The forces and moments applied by the end effectors of robots can be estimated with the use of force/torque sensors mounted on the wrists of respective robots. Figure 4 schematically shows the forces and moments acting on a robot gripper [2, 3, 5].

The following equations relate the forces and moments sensed by the force/torque sensor to the forces and moments experienced by the end effectors tip.

$$m_G \cdot \vec{c} = \vec{f}_s + \vec{f}_e + m_G \cdot \vec{g} \, , \tag{8}$$

$$I_G \cdot \vec{\omega} + \vec{\omega} \times I_G \cdot \vec{\omega} = \vec{n}_s + \vec{r}_s \times \vec{f}_s + \vec{n}_e + \vec{r}_e \times \vec{f}_e \, , \tag{9}$$

where $\vec{c}$ is the position vector of the $C.G$ of the gripper with respect to the world reference frame; $\vec{f}_s$ and $\vec{n}_s$ are respectively the force and moment sensed by the force/torque sensor; $\vec{f}_e$ and $\vec{n}_e$ are the force and moments respectively experienced at tip of end effectors; $\vec{r}_s$ is the vector from $C.G$ of gripper to the center of force/torque sensor; $\vec{r}_e$ is the vector from $C.G$ of gripper to the center of end effectors; m_G is the mass of gripper; I_G is the moment of inertia of the gripper; ω is rotational velocity of the gripper.

For the end effectors force estimation and end effectors moment estimation the process equation of Kalman Filter is:

$$X(k) = A \cdot X(k-1) + B \cdot U(k) + w(k) . \tag{10}$$

And the measurement equation is:

$$Y(k) = H \cdot X(k) + v(k) , \tag{11}$$

where k denotes the time instant and $X(k)$ is the state vector representing the force to be measured (f_e).

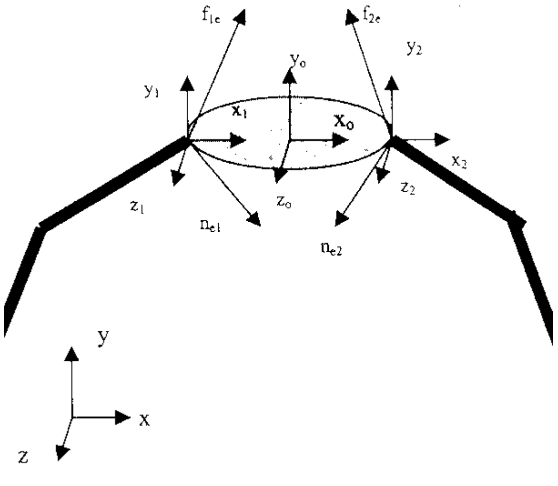

Fig. 4. Manipulator Payload Dynamics of a Closed Chain Robotic System.

The noise covariance matrices are given by:

$$Q = E\left\{ w(k) w(k)^T \right\} = [0.001] , \tag{12}$$

and

$$R = E\left\{ v(k) v(k)^T \right\} = [0.001] . \tag{13}$$

Noise covariance matrices Q and R represent a measure of confidence in the process equation (dynamics) and the measurement respectively; $U(k)$ is the vector representing the acceleration (mm/s^2) of center of gravity of the gripper in three directions and $Y(k)$ is the force measured by the sensor in three directions. $U(k)$ is given by the following equation:

$$U(k) = I_G \cdot \vec{\omega} + \vec{\omega} \times I_G \cdot \vec{\omega} - \vec{r}_s \times \vec{f}_s - \vec{r}_e \times \vec{f}_e \, . \tag{14}$$

4. PRINCIPLES CONCERNING ROBOTS

These new principles are based mainly on the fact that robot work abilities can be designed and optimized to best fit the task objectives.

Reduce the robot’s structural complexity i.e. minimizes the number of arms and arm joints that are determined by the number of hand orientations. For different types of robot kinematics chains, task motions well require moving a different set of joints. To calculate the AJU (arm joint utilization) of a given robot performing a given task it is assumed for simplicity that a unit move is equivalent to both 1^0 and $1\,mm$. A measure of drive system effort is generated by a weighted mean of the average AJU at each joint.

$$AJU\ Measure = \sum_{j=1}^{N} \left(0.5 d\theta_1 + 0.33 d\theta_2 + 0.17 d\theta_3 \right) , \tag{15}$$

where N is number of motion by the robot, $d\theta_i = \theta_{ij} - \theta_{i(j-1)}$, i is joint number, $i = 1, 2, 3$, j - position, $j = 1, \ldots, N$.

Because the motions of each robot model are different the AJU measure estimates for any given task are different. A relatively lower AJU would be more desirable.

Minimize the number of sensors, because each sensors adds to installation and operating costs by additional hardware, information processing.

Simplify the necessary motion path. Point-to-point motion requires simpler control of positioning and velocity compared with continuous path motion.

Arm joint accuracy (AJA). The AJA measures the accuracy of the robot arm during motion. In point-to-point tasks the accuracy is important not the end of the motion while in continuous path tasks accuracy is an important measure throughout the motion. Calculation of AJA is as follows:

$$AJA\, Measure = \sum_{j=1}^{N} \int_{t_{j-1}}^{t_j} \left(k_1 \cdot \varepsilon_1 + k_2 \cdot \varepsilon_2 + k_3 \cdot \varepsilon_3 \right) dt \, , \tag{16}$$

where *N* is number of motion by the robot, k_i joint *i* kinematics coefficient, which also depends on link geometry, ε_i is the difference between the reference and actual position of joint *i*, $t_{j-1} - t_j$ is the time during which the robot moves from position *j* - 1 to position *j*.

A lower value AJA implies a relatively better accuracy estimate and provides another way to compare the performance of alternative robot models [4].

The vertically articulated robot has the best (minimum) arm joint utilization when comparing specific work positions; the cylindrical robot has the most wasteful (maximum) joint utilization; the SCARA robot has the best overall joint utilization for all reachable work position followed by the vertically articulated robot.

For a flat work surface vertically articulated robots have the best overall reach ability, reaching the maximum number of positions and orientations compared with cylindrical, spherical and SCARA robots.

For some task, the SCARA robot performs the fastest overall; the cylindrical robot performs the slowest.

The work position relative to the robot base affects robot performance in terms of motion accuracy and load. For a small, vertically articulated robot the height level of the work area has little impact, while the distance from the base does; when the distance increase, the effort (AJU, AJL) increases, but the accuracy (AJA) improves.

Arm joint load (AJL) estimates the load to which the arm is subjected during task motions. If is calculated as follows:

$$AJL\ Measure = \sum_{j=1}^{N} \int_{t_{j-1}}^{t_j} \left(T_1 + T_2 + T_3\right) dt\,, \qquad (17)$$

where *N* is number of motion by the robot, $t_{j-1} - t_j$ is the time during which the robot moves from position $j-1$ to position *j*, T_i is the moment applied on joint *i* during motion.

Despite the relatively large work volume of each robot, the work area which is reachable is limited. Therefore, the selection of the work-surface location and orientation has significant influence on the robots performance.

Horizontal travel through a work position is significantly more efficient than vertical travel for the majority of work positions for small and medium vertically articulated robots, medium and large spherical robots and the SCARA robot.

5. CONCEPTS AND TRENDS

Based on approach experience and methodology, the research efforts on the cooperative robots can be categorized according to a number of distinguishing factors:

- Identical robots groups versus variety groups.
- Unit being complete robot versus modular units combining to form a robot.
- Centralized control systems (center for intelligence) versus decentralized (distributed intelligence).

Following are some of these issues in the form of questions:

- What is a good cooperative robots size?
- Should the robot members be specialized or multitasked?
- Should there be leadership in cooperative robots, and if so, in what form?
- How should the cooperative robots be structured?
- What rules govern the cooperative behavior of the robots?
- How can the cooperative robots performance be enhanced?
- How can cooperative robots be realized for real applications?

REFERENCES

[1] Sun, D., Mills, J. (2002). *Manipulating Rigid Payloads With Multiple Robots Using Compliant Grippers*, IEEE/ASME Transaction Mechatronics, Vol.7, No. 1

[2] Kumar, M., Garg, D. (2004). *Sensor-Based Estimation and Control of Forces and Moments in Multiple Cooperative Robots*, Transactions of the ASME journal of Dynamic Systems, Measurement and Control, Vol. 126.

[3] Zivanovic, M., Vukobratovic, M. (2004). *Synthesis of Normal Motion of the Multi-Arm Cooperating Robots with Elastic Interconnections at the Contacts*, Transactions of the ASME Journal of Dynamic Systems Measurement and Control, Vol. 126.

[4] Pennock, G., Mattson, K. (1997). *Analytical and Graphical Solutions to the Forward Position Problem of Two Robots Manipulating a Spatial Linkage Payload*, Journal of Mechanical Design, Vol. 119.

[5] Zhang, X., Yu, Y. (2004). *Dynamic Analysis of Planar Cooperative Manipulators with Link Flexibility*, Journal of Mechanical Design, Vol. 126.

[6] Dorin, A., Dobrescu, T. (2002). *A Method for General Optimum Trajectory Planning of Multiple Robotic Arms*, Proceedings of the International Conference on Manufacturing System, Romanian Journal of Technical Science, Tom 47, pp. 343-346.

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