Proceedings of the 1997 IEEE
International Conference on Robotics and Automation
Albuquerque, New Mexico - April 1997

Object Resolved Teleoperation*

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Abstract

A control concept referred to as *object-resolved teleoperation* is introduced in this paper in which motion or force is imparted to a remote object in order to achieve a desired action by the object. The object might be a hand-held tool or an airplane and the desired interaction might be control of its spatial position or interaction with the environment. The human interface to the master is a hand-held proxy for the object. At the remote site, the object motion or force commands are resolved into the appropriate commands for the actuation system. The potential advantages of ORT are: 1- improvement in human-machine interaction, the consequence of the operator's cognitive task and command response being identical to those he would perform if he were manipulating the object, 2- the opportunity to share control between the operator and an intelligent controller at the remote site in such ways as to make best use of the capabilities of each. In this paper, application to grasp and manipulation is discussed.

1 Introduction

The combined control of a remote physical system by a human and a mechanical or electronic device has been variously called: 1- telerobotic control [14], 2- computer-aided teleoperation [17] and 3- teleautonomy [3]. Each definition assumes that the remote system is (or can be) intelligent and capable of sharing cognition with the human operator. The level of participation of the human can range from oversight or supervisory control to direct or full manual control. The term *shared control* is used to describe human participation when some variables or functions are supervised and some are manually controlled. The term *traded control* is used to describe human participation in which there is temporal sharing of responsibility with the computer controller.

Shared and traded control between and human and an autonomous controller in tasks of haptics and manipulation is currently a subject under intense investigation. Undersea exploration, medical diagnosis and minimally invasive surgery, and vehicle flight control are relatively unstructured applications where the human plays a significant role. The exact form of human participation depends on the application, the capability and training of the human operator and the level of technology required for the autonomous controller. In factory automation, the trend has been to automate only the highly structured tasks; the human role is that of supervision. It has been conjectured by some [1] that shared control, which makes real-time use of human intelligence, may hasten the extent of factory automation by encompassing more unstructured tasks.

Function-based shared control has been proposed by Tarn et al [16] as a means to achieve performance not achievable by either a human or autonomous control alone and they identified applications in obstacle avoidance, hybrid force/position control and dual arm coordination where it can be beneficial. Michelman and Allen [6] applied shared control to a multi-fingered mechanical hand in order to overcome the difficulties associated with direct mapping of finger joint motions. They proposed a method in which the input device commands the motion of the object being grasped with a set of grasp primitives that the operator learns to use rather than commands to the joints of the fingers. An autonomous capability at the hand translates the primitives into a coordinated hand response. Similar difficulties associated with multi-fingered grasp have led the Fuentes and Nelson [2] to develop "virtual tools" as a means to simplify the man-machine interface.

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Several researchers have investigated the use of object-based coordinates to formulate control laws for object manipulation [9, 8, 12]. Application of task-based coordinates in teleoperation has been postulated by Sepehri [13] as a means to improve the man-machine interface of heavy construction equipment. Hui and Gregorio [5] have proposed use of a virtual handle, which is a hand-held replica of the object being manipulated, in order to improve the transparency of remote grasp and manipulation.

Efforts to improve the man-machine interface in teleoperation are numerous. Teleprogramming has been demonstrated as an effective means to overcome the time delay inherent in remote control by incorporating predictive graphics at the master console and reactive capability at the remote site [10].

Improvement in master performance has concentrated on the use of force reflection. The PER-Force [7] is a commercially available six degree of freedom, hand-held master that is typically applied to bilateral control of a single remote manipulator. The Phantom is a commercially available force reflecting master which interacts with the fingertip of the operator to provide three degrees of force reflective control [11].

2 Description of ORT

The name object-resolved telerobotics (ORT) derives from the form of the operator-master interface. The master, sometimes referred to herein for emphasis as the proxy, has a hand-hold interface with the general shape of the remote object being controlled.[1] Object-based commands are generated when the operator moves or applies force to the proxy (with one or both of his hands) At the remote site, the object commands are resolved into the appropriate slave manipulator commands by the slave controller. One of the principal advantages of ORT is (speculated) improvement in human-machine interaction, the consequence of the operator's cognitive task and command response being identical to those he would perform if he were manipulating the object. Reaction time and workload should be reduced because the controller is more intuitive and learning time should be reduced because it is not necessary to learn the characteristics of the slave.

[1]The Spaceball, produced by CIS Graphics, Inc., is an example of a master that, strictly interpreted, would be a proxy for any spherical object to be remotely controlled. Being less restrictive in definition of a proxy, it can represent any rigid object, although it fails to give the operator a haptic sense of shape and orientation of the object and being fixed, fails to give any sense of compliance of the object.

The most compelling application for ORT is when object control cannot be accomplished by either the operator or computer acting alone. And in this application lies the second principal advantage of ORT: the opportunity to parse control between the operator and an intelligent controller at the remote site in such ways as to make best use of the capabilities of each. The operator typically is given real-time control authority over low frequency aspects of a task (eg. object position commands in manipulation and in piloting an aircraft) in order to reduce the communication bandwidth required and to minimize the deleterious effects of time delay for long-distance communication.

The operator is nominally responsible in real-time for control of one or more degrees of manipulative freedom of the object and may receive kinesthetic feedback of some object response. He is also "on call" to respond to emergency situations. An intelligent controller aids the operator in task accomplishment and is typically given control authority over high frequency aspects of the task (eg. grasp).

The nominal responsibilities of the computer based controller are: 1) control of the manipulative freedom of the object not assigned to the operator, 2) distribution of the manipulative commands to the appropriate slave and slave actuation devices including redundancy resolution when aggregate manipulative freedom exceeds object cartesian freedom. Maintaining grasp stability in a multi-finger grasp is an example of redundancy resolution.

Four potential applications are listed below in which the operator shares manipulative control of an object with an intelligent controller at the remote site:

Precision grasp the object is the item being grasped and shared control is necessary because the operator does not have the response fidelity to remotely maintain grasp stability and perform precision placement of the object when in contact with its environment.

Unmanned aerial vehicles the object is the aircraft and shared control is necessary because the operator does not have the somatosensory feedback necessary to adequately coordinate control of the aerodynamic control surfaces and throttle using the conventional input devices.

Spacecraft maneuvering the object is the spacecraft and shared control is used to maintain operator attentiveness to an otherwise automated task.

Aerial refueling the object is the nozzle that is to be inserted in a receiver aircraft and shared control is required because the operator does not have the response capability to stabilize the nozzle in the presence of aerodynamic disturbance.

The spacecraft meneuvering application has been formulated and investigated by simulation in reference [15]. In this paper, application to grasp and manipulation is discussed and the control architecture formulated for a simple two-finger task.

2.1 Object equations of motion

In each of these applications, the object can be considered a single rigid body whose motion or force of interaction with the environment is to be controlled. Using the formulation developed in reference [12], the equations of motion for a single rigid object are:

$$I_0\ddot{\phi} + Q_0 = WF + F_{ext} \tag{1}$$

where I_0 is the inertia tensor of the object, $\dot{\phi}$ is the linear and angular velocity of the object with respect to the absolute coordinates, Q_0 is a force and moment vector that includes gravity and the nonlinear Euler equation inertia effects of centripetal and Coriolis acceleration, W is a grasp matrix which pre-multiplies to transform the contact forces and moments into equivalent forces and moments at the object center of mass, F is the vector of forces and moments applied to the object by each manipulation device or actuation device[2] and F_{ext} is the resultant force and moment applied at the object center of mass as a result of object contact with the environment.

2.2 Object-based control architectures

Object impedance control as developed by Schneider and Cannon [12] and coordinative manipulation as developed by Nakamura [9] and Murray, Li and Sastry [8], are the basis for ORT. Control laws are written for state variables ϕ of equation 1. Figure 1 is fashioned after that of figure 6.3 of [9] to indicate how the control signals to each of "i" manipulators (robotic mechanisms) that contact the object are broken into two paths that produce: 1- the force required to grasp and manipulate the object and 2- the end-effector position required to have the "unloaded" manipulator track the contact point. This architecture permits separate control laws to be formulated for the object and each device which manipulates the object. For remote control, the communication variables are object state and the master can be a proxy to the object to be manipulated. Not shown are the controls applied to each robotic mechanism to accomplish the object motion and not shown is any kinesthetic feedback to the operator.

The object controller as defined in the previous section has three significant limitations when the the task is to remotely perform precision grasp and manipulation: 1- force distribution between finger contacts to the object is established by use of the pseudoinverse and internal (nullspace) force must be preset by the user at a (high enough) level to assure grasp stability, 2- the control algorithm does not include feedback of contact force to assure that the desired level of grasp stability is attained and 3- the response speed of "finger-like" manipulators are generally inadequate for precision control of grasp forces.

Figure 2 is a block diagram representation of ORT with coordinated coarse/fine control. The basic architecture of two paths is retained. The primary differences with the previous architecture are: 1- the addition of a second set of fingertip actuators that are physically in series with the first set but which have a higher response bandwidth, 2- the inclusion of kinesthetic feedback to the operator of the net force Q on the object and 3- the introduction of a real-time algorithm, denoted contact force allocation in figure 2. The contact force algorithm determines the actuation forces required to accomplish the commanded object motion *and* maintain grasp stability with a near-minimum norm level of internal force [4]. Use of the coarse/fine architecture in conjunction with resultant force reflection to the operator provides a form of task sharing between the operator and remote computer. The operator controls object position explicitly while the force feedback loop about the fine actuator at the object site assures grasp stability.

The object is placed under impedance control, as described in reference [12], so that it can handle disturbance forces and modeling errors. The fine actuators operate in explicit force control and in a mode amenable to change of position (length) while maintaining the commanded force. The desired position of the coarse actuators is controlled so as to maintain the fine actuators, which typically have an inadequate range of motion to accomplish the task alone, near the

[2] Finger contacts produce moments and forces depending on there structure as do aircraft thrust and aerodynamic lift surfaces.

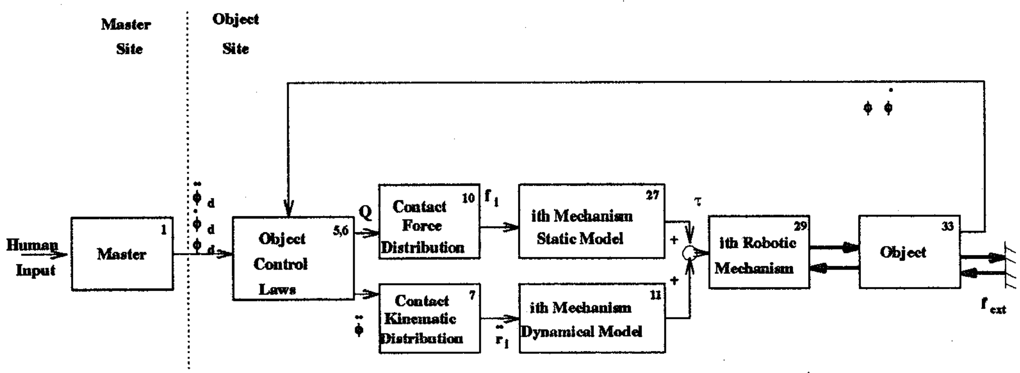

Figure 1: Adaptation of object control for teleoperation.

center of their range of motion.

In appendix A, the ORT control architecture is presented for a simple grasp task. For a spatial grasp task, the concept presumes the presence of fingertip actuation and sensor devices that can apply and sense force, respectively, both normal and tangent to the contact plane and that have a very high bandwidth. Such devices do not presently exist.

3 Summary

The ORT control architecture has been presented which provides an intuitive operator interface and permits shared control with a range of options for operator and computer involvement.

Appendix A- Application to a simple grasp model

Consider the simple grasp model of figure 3 with a pair of actuators on each side of an object acting serially. The vector ϕ becomes a one element vector x_0 and the equation of motion (1) of the object with mass m_0 reduces to:

$$m_0\ddot{x}_0 = f_{01} - f_{02} + f_{ext} \tag{2}$$

where f_{0i} is the force applied to the object by the i^{th} fine actuator. The coarse (A_{ci}) and fine (A_{fi}) actuators are modelled as force applicators each with a distal mass. The equations of motion of the actuation systems are:

$$m_{f1}\ddot{x}_{f1} = f_{f1} - f_{01} \tag{3}$$

$$m_{f2}\ddot{x}_{f2} = f_{02} - f_{f2} \tag{4}$$

$$m_{c1}\ddot{x}_{c1} = f_{c1} - f_{f1} \tag{5}$$

$$m_{c2}\ddot{x}_{c2} = f_{f2} - f_{c2} \tag{6}$$

where x_{ci} and x_{fi} are the absolute position of the coarse and fine actuators, respectively, and f_{ci} and f_{fi} are the forces applied by their active elements. Equations 2, 3 and 4 are valid provided masses m_{fi} remain in contact with the object.

Define the nominal pose to be with the object centered at $x_s/2$, with each fine actuator at the center of its range of motion, with no external force applied to the object and with a specified level of internal force applied to the object. In general, the coarse actuator will be nominally posed at other than the center of its range of motion. With the range of motion of the fine actuator denoted x_{fr}, the desired pose of the fine actuator can be written

$$x^d_{f1} - x^d_{c1} = x_{fr}/2 \tag{7}$$

$$x^d_{c2} - x^d_{f2} = x_{fr}/2 \tag{8}$$

where, for convenience, the length of the fine actuator is assumed to be zero when it is fully retracted. Then, at any time the error in pose can be written

$$e_{c1} = -x_{fr}/2 + (x_{f1} - x_{c1}) \tag{9}$$

$$e_{c2} = x_{fr}/2 - (x_{c2} - x_{f2}) \tag{10}$$

Computations indicated in each block[3] in figure 2 will now be stated for the simple grasp model of figure 3.

[3]The block numbers correspond to those in figure 2.

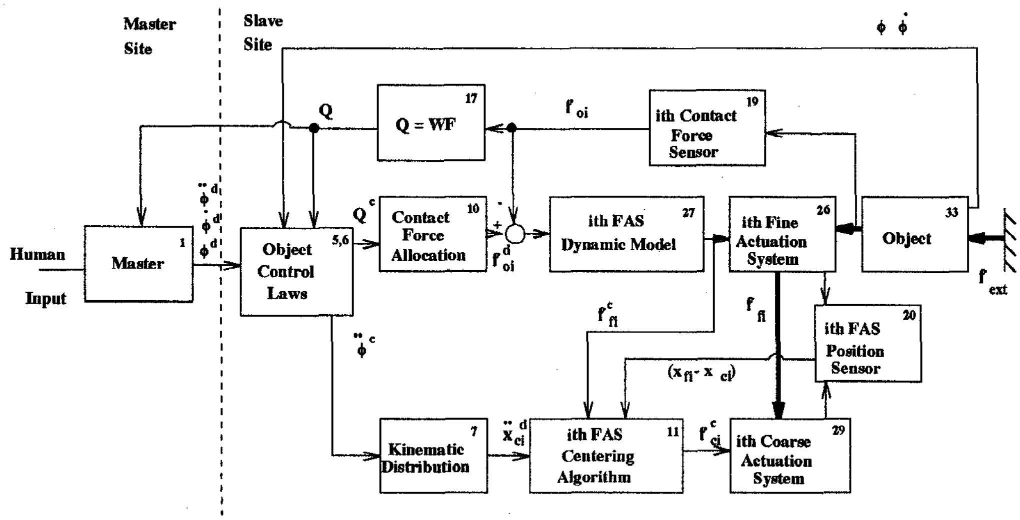

Figure 2: Block diagram of ORT for precision grasping.

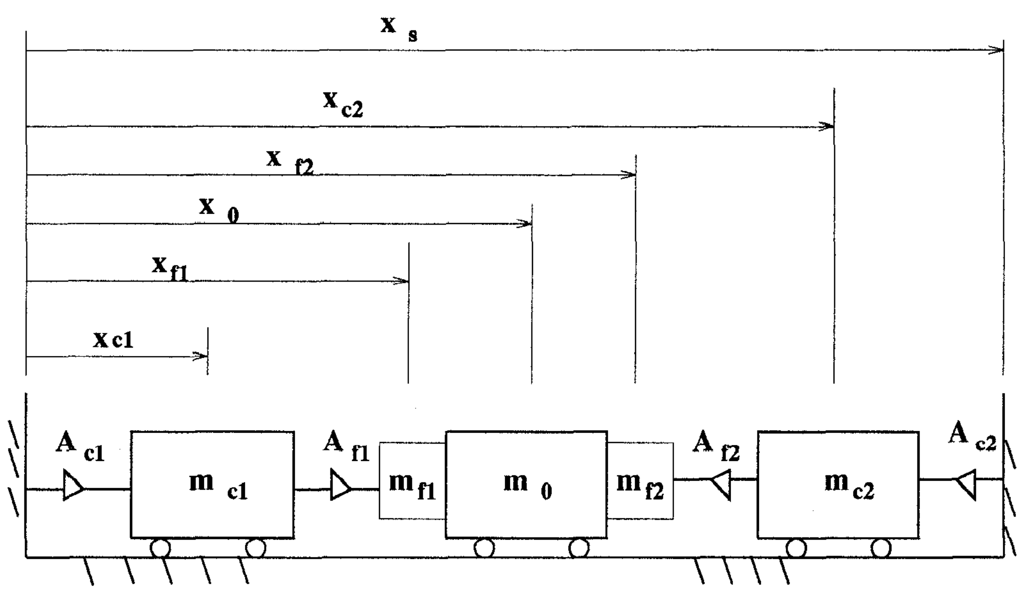

Figure 3: Simple grasp model with serial actuation.

Block 33 "Object" Equation (2) is the model of the object.

Block 26 "i^{th} FAS" Equations (3) and (4) are the model of the fine actuation systems.

Block 29 "i^{th} CAS" Equations (5) and (6) are the model of the coarse actuation systems.

Block 6 "Object kinematic control law" Choose an impedance characteristic for the object

$$\hat{m}_0 \ddot{x}_o = f_{ext} + f_{imp} \tag{11}$$

where

$$-f_{imp} = K_v(\dot{x}_0 - \dot{x}_0^d) + K_p(x_0 - x_0^d) \tag{12}$$

Then, the commanded acceleration $\ddot{x}^c$ can be evaluated with equation 11 where the external force is determined from equation 2 with acceleration approximated by its previous or desired value and f_{imp} determined from equation 12.

Block 5 "Object force control law" The commanded object force $Q^c = [f_{01}, -f_{02}]$ is evaluated by eliminating $\ddot{x}_0$ from equations 2 and 11.

Block 7 "Kinematic distribution" Differentiating equations 7 and 8 twice yields $\ddot{x}_{ci}^d = \ddot{x}_{fi}^d$. The acceleration of the contact points on the object are computed from the acceleration of the object center of mass using the kinematic relation $\ddot{x}_0 + \dot{\omega} \times p_i + \omega \times (\omega \times p_i)$ where p_i is the vector position of the i^{th} contact relative to the center of mass and $\ddot{x}_0$ is determined from $\ddot{y}_0$ based on the relation of center of masses of the virtual object and object (as in object impedance control). For the simple grasp model this is the acceleration of the tip of the fine actuator $\ddot{x}_{fi}$ provided contact is not lost. Then,

$$\ddot{x}_o^d = \ddot{x}_{fi}^d = \ddot{x}_{ci}^d \tag{13}$$

Block 10 "Contact force allocation" The force $Q = WF$ can be distributed to the contact points by performing the pseudoinverse

$$F = W^{\#}Q + F_{int}^d \tag{14}$$

where the desired internal force F_{int}^d must be specified.

Block 27 "i^{th} FAS Dynamic Model" Each force f_{0i} is directed to the fine actuator via a dynamic model that converts it into "joint torques" (i.e. into the equivalent forces f_{fi} on each fine actuator). For the simple grasp model the equivalent force at each actuator is determined using equations 3 and 4

$$f_{f1}^c = f_{01}^d + m_{f1}\ddot{x}_{f1}^d \tag{15}$$

$$f_{f2}^c = f_{02}^d - m_{f2}\ddot{x}_{f2}^d \tag{16}$$

Block 11 "i^{th} FAS centering algorithm" e_{ci}, the difference between FAS pose and FAS nominal pose given by equations 9 and 10 can be used to drive the coarse actuators where x_0 is the desired object position and x_{ci} is assumed to be measured by the i^{th} actuator. For more accuracy in control of the coarse actuators, an inverse dynamics controller that incorporates feedforward of the desired acceleration of the interface with the fine actuator $\ddot{x}_{ci}^d$ and force of interaction with the fine actuator f_{fi}^c should be included. Use equation 5 and 6 to define control torques:

$$f_{c1}^c = \hat{m}_{c1}u_1 + f_{f1}^c \tag{17}$$

$$f_{c2}^c = -\hat{m}_{c2}u_2 + f_{f2}^c \tag{18}$$

and choose to use a PD with tracking control law:

$$u_i = \ddot{x}_{ci}^d + k_{civ}\dot{e}_{ci} + k_{cip}e_{ci} \tag{19}$$

When equation 19 is inserted in equations 17 and 18, the centering algorithm results:

$$f_{c1}^c = \hat{m}_{c1}(\ddot{x}_{c1}^d + k_{c1p}e_{c1} + k_{c1v}\dot{e}_{c1}) + \hat{f}_{f1}^c \tag{20}$$

$$f_{c2}^c = -\hat{m}_{c2}(\ddot{x}_{c2}^d + k_{c2p}e_{c2} + k_{c2v}\dot{e}_{c2}) + \hat{f}_{f2}^c \tag{21}$$

Note the error terms, which attempt to center the fine actuators are under computer control and the commanded acceleration, $\ddot{x}_{ci}^d$, is an additional means for operator input.

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