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On the Formulation of Parallel Position/Force Control Schemes for Industrial Manipulators

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Keywords: *position/force control, impedance control, admittance control, hybrid control*

Abstract

In this paper, three commonly-used position/force control schemes namely Impedance, Admittance and Hybrid Position/Force control are investigated for use in industrial manipulators. In order to eliminate the instability problem that may occur in the customary versions of these schemes for large position errors, a modification is proposed, which is based on determining the joint-space position errors using inverse kinematic solutions rather than using the inverse Jacobian matrix. The feasibility of this modification relies on the fact that almost all of the industrial manipulators have easily obtainable inverse kinematic solutions. The simulation results showing the performance of the modified control schemes are also presented as applied on a Puma 560 manipulator.

1. Introduction

These days the robots are required to com ply with their environment more often than ever. This calls for new robot architectures with m ore sensors and control schemes which not only control the position s of the robot m anipulators but also the forces exerted by th em to the environment. Comm only encountered schem es in the related literature that m ay be used to control th e position an d the applied f orces a nd/or m oments are the Im pedance, Hybrid Position/Force Control and the Ad mittance Cont rol [1]. However, in these s chemes, the position error is formed by comparing the reference input (desired position) and the measured data (actual position) with each other in the Cartesian space. This error is transformed into the joint space as a lin ear approxi mation by using the inverse of the Jacobian m atrix. The approximate error calculated in the joint space is then fed into the control unit to drive th e joint actuators. This m ethod can be used to c ontrol the m anipulator succ essfully if the error calculated in the Cartes ian space is sm all. The sy stem behavior deterio rates and it may even become unstable as this error increases. It is a known fact that, the inverse kinematic solutions can be obtained quite easily fo r m any m anipulators used in practice [2], [3]. The exact position error for such a m anipulator can be ev aluated directly in th e joint spa ce by f irst finding the joint space equivalen ts o f the desi red and actual position s separately th rough the inverse kinematics and then comparing them.

Necessary modifications are proposed in this pa per to be incorporated into the custom ary Impedance, Hybrid Position/For ce Control and the Adm ittance Control schem es to evaluate position error directly in the joint space as described above. The modified control schemes are tested in simulation f or cer tain ta sks. Sim ulation results a re pre sented to dem onstrate the performance achieved with these modifications.

2. Problem Definition

Restricting one or m ore of the m anipulator's motion along certain directions, while it performs a desired m otion, by applying forces in those directions m ay cause instability [4].

Unlike the simple modification introduced in [5, 6], many of the researchers in this area have so far concentrated generally on making the conventional position/force control schemes more sophisticated by introducing adaptive or learning features [7, 8] in order to cope with this problem. While forming such sophisticated controls, the comparison methods for calculating the position errors of the customary position/force control schemes are kept unmodified. The possible instability due to the customary control schemes is discussed in the MSc thesis of Dede [5]. The instability problem for the customary position/force control schemes arises when there are increases in the errors calculated for the position-controlled subsystem in the Hybrid Position/Force Control scheme and for the position-controlled inner control loop in the Impedance and Admittance Control schemes. This is basically due to the previously mentioned fact that the position errors in the joint space are obtained approximately by the linear transformation of the actual position errors in the Cartesian space through the inverse Jacobian matrix.

3. Customary Position/Force Control Schemes

In this section the customary schemes for position/force controllers are introduced as they are used in the related literature. The first control algorithm discussed is the Impedance Control which is followed by the Admittance and Hybrid Position/Force Control.

3.1 Customary Impedance control

The objective of impedance control is to establish a desired dynamical relationship between the end-effector position and the applied force [9]. The relationship between the velocity $\dot{X}$ and the applied force F is referred to as the mechanical impedance, Z_m. In the s domain, this is represented by

$$F(s) = Z_m(s)\dot{X}(s). \qquad (1)$$

Equation (1) is rewritten to relate the position, $X(s)$, to the force by

$$F(s) = sZ_m(s)X(s). \qquad (2)$$

Desired impedance is specified as;

$$sZ_m(s) = Ms^2 + Ds + K. \qquad (3)$$

The constant matrices M, D and K represents the desired inertia, damping and stiffness values, respectively. Typically, as in this case, the target impedance is chosen as a linear second-order system to mimic mass-spring-damper dynamics [4]. The task of Impedance control is to guarantee the behavior of the controlled system to be as dictated by equation (3). Impedance control has been implemented in various forms, depending on how the measured signals including velocity, position or force are used.

The order of the impedance control depends on how the impedance term is defined. If the impedance term is defined as a spring, then the control scheme is called a zeroth-order Impedance control, which is commonly known as the Stiffness control [10]. Second-order Impedance control that is applied to a position-based control system is shown in Figure 1, in which X_F represents the equivalent force-feedback trajectory, X_I is the modified desired trajectory defined as the solution to the differential equation

$$M\ddot{X}_I + D\dot{X}_I + KX_I = -F + M\ddot{X}_D + D\dot{X}_D + KX_D, \qquad (4)$$

where $X_I(0) = X_D(0)$, $\dot{X}_I(0) = \dot{X}_D(0$. M, D and K are as defined before. Equation (4) can be obtained by inspection from Figure 1. It implies the same impedance definition as in equations (2) and (3). It is noted that in the Impedance control formulation X_I is a function of both the input, X_D, and the measured contact force, F. Since the position-controlled subsystem ensures that the end-effector position X closely tracks X_I defined in equation (4), the target impedance of the manipulator is obtained [11].

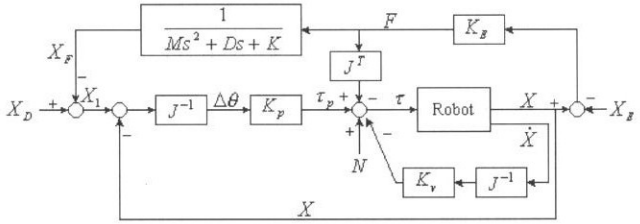

Fig.1. Customary position-based second-order Impedance Control scheme

In Figure 1, and in the following Figures 2, 3, 4, 5 and 6, "N", represents the feed-forward torque input to counteract the centrifugal, Coriolis and gravitational forces [11]. The other feed-forward torque input "$J^T K_E(X - X_E)$" is generated to counteract the effect of the environmental interaction forces [7]. Here, "K_E" is the combined stiffness matrix of the environment and the force sensors. In this work, however, environment is modeled as rigid, and therefore, "K_E" is associated only with the force sensors.

Sensor-based feedback-controlled interaction with the environment requires the impedance to be of second order at most. The reason for this is that the dynamics of a second-order system are well understood and familiar and for higher-order systems, it is difficult to obtain measurements corresponding to the higher-order state variables [13].

3.2 Customary Admittance control

Admittance control specifies a force setpoint, which is tracked by a force compensator. In contrast with a pure position control, which rejects disturbance forces in order to track a given reference motion trajectory, the force compensator attempts to comply with the environmental interaction and reacts quickly to contact forces by rapidly modifying the reference motion trajectory [14]. The mechanical admittance is defined as

$$\dot{X}(t) = AF(t). \quad (5)$$

This equation can be written in the s domain as

$$X(s) = K(s)F(s), \qquad (6)$$

where

$$K(s) = \frac{1}{s}A. \qquad (7)$$

In equations (5), (6) and (7), X and $\dot{X}$ are the positio n and velocity vecto rs of the end-effector, A is the adm ittance m atrix, and Figu re 2 shows the structur e of a custom ary admittance control scheme.

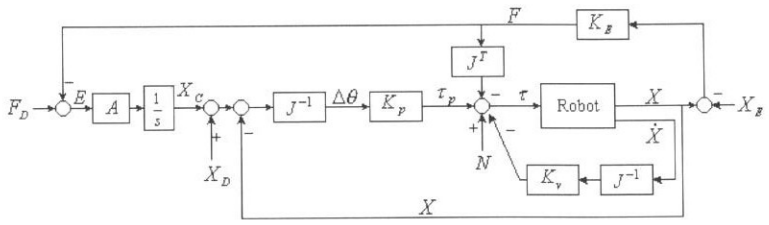

Fig.2. Customary position-based Admittance Control scheme

The admittance matrix, A, in Figure 2, relates the f orce error v ector, E ($E = F_D - F$), to the required m odification in the end-effector v elocity ve ctor. This le ads to the f ollowing additive modification on the reference trajectory:

$$X_c = \int A(F_D - F)dt . \qquad (8)$$

Admittance contro l can be effectively a nd precisely achieved by choosing a suitable A matrix for t he known s tiffness of t he environm ent. Howe ver, if the working environm ent changes significantly, A matrix should be recalculated in order to adapt the new environment. Changing th e adm ittance value pro perly due to the changing environ ment m ay be realize d with adaptive control laws. In general, t hough, it can be said that the value of the A matrix should decrease as the stiffness of t he environment increases causing larger am ount of forces to be exerted with the sam e amount of motion toward the surface. An adaptation to changing environments is also necessary for selecting the impedance term in Impedance control.

Although equations (5)-(8) im ply that A is c onstant, it is also possible, and in fact expedient, to extend the concept of admittance to involve a variable matrix such as

$$A(s) = k_d s^2 + k_p s + k_i , \qquad (9)$$

which then results in the following PID force compensator:

$$K(s) = \frac{1}{s} \cdot A(s) = k_d s + k_p + \frac{k_i}{s} . \qquad (10)$$

3.3 Customary Hybrid Position/Force control

Combining position and f orce inf ormation into one contro l scheme f or m oving the end-effector in nondeterm inistic environm ents has been introduced as hybrid position/force control [15]. The advantage of hybrid position/f orce control with respect to others is that the position and force inform ation are processed inde pendently by separate controllers to take advantage o f well-known control techniques for each of the m. The outcom es of these controllers are then combined only at the final stage when both have been converted to joint torques [16]. Figure 3 s hows the ap plication of the hybrid p osition/force control scheme as a block diagram.

In Figure 3, $S = diag(s_j)$ $(j = 1...n)$ is calle d the com pliance se lection m atrix, n represents the degree o f freedom. The m atrix S determines the subspaces in which force or position are to be controlled, and s_j is selected as either 1 or 0. When $s_j = 0$, force contro l must be used in the j^{th} direction of the Cartes ian space; oth erwise, pos ition con trol m ust be used in that direction. De pending on the required task, S matrix can be constant, or it can change in time according to the varying grad ient of the task surface and the path followed on it [17].

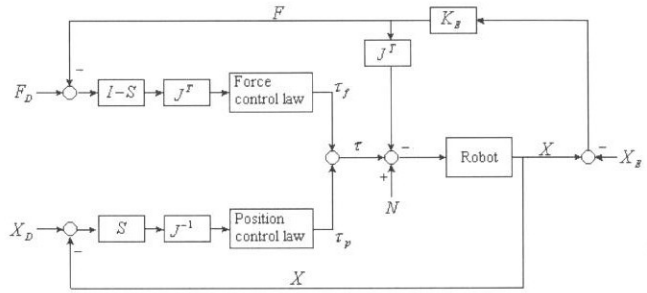

Fig. 3. Customary Hybrid Position/Force Control scheme

For each ta sk configuration, a generaliz ed surface can be de fined with position constraints along the normals to this surface and force constraints along the tangents. This means that the end-effector cannot move along the normals into the surface and cannot cause reaction forces to arise along the tangents of the surface. These two types of constraints partition the freedom directions of possible end-e ffector motions into two orth ogonal sets along which either position or f orce contro l m ust be u sed [14]. U tilizing this partition ing, S matrix is formed appropriately in accordance with the required task.

In this control scheme, the command torque is

$$\tau = \tau_p + \tau_f \qquad (11)$$

τ_p and τ_f are th e com mand torques acting in th e position and force subspaces , respectively. In this way, pos ition contro l and force control are d ecoupled. In g eneral, it happens that PD action is satisfactory for posi tion control, and PI action is satisfactory for force control [1].

4. Modified Position/Force Control Formulations

As pointed out above, for position control, PD action is preferred in both of the Hybrid and Admittance control schemes. However, in the customary versions of these schemes, as seen in Figures 1, 2 and 3, the Cartes ian-space position error ($X_{ref} - X$) is a ssumed to be sm all and therefore it is transformed into the joint space approximately as

$$(\theta_{ref} - \theta) \approx J^{-1}(X_{ref} - X) . \qquad (12)$$

It turns out that this approxim ation often l eads to unsatisfactory behaviors if the position error beco mes large. A s a propo sal of rem edy, the Im pedance, A dmittance a nd H ybrid

Position/Force control s chemes are m odified here as desc ribed below . This m odification is based on calculating the joint-space position error exactly as follows:

$$(\theta_{ref} - \theta) = IK(X_{ref}) - IK(X). \qquad (13)$$

Here, " IK " symbolizes Inverse Kinematics and this m odification is of course feasible for those manipulators for which " IK " solutions are easy to obtain. Fortunately though, alm ost all of the industrial manipulators are of this kind [2], [3].

4.1 Modified Impedance control

Inner position loop of the Im pedance Control sc heme is modified to make the necessary comparisons in the join t space and not in th e Cartes ian sp ace as it was for the cu stomary version. Figure 4 shows the modified version of the Impedance Control scheme.

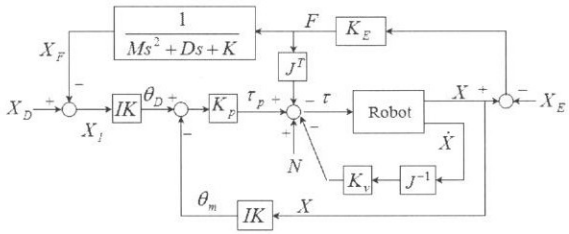

Fig.4. Modified Impedance Control scheme

Position f eedback of the end-ef fector is ch anged to jo int position f eedback by in verse kinematics " IK " in the m odified scheme. The invers e kinematics solutions can be achieved easily by using the methodology introduced in [2]. Besides, in a real time application, position feedbacks are received directly from the joint transducers. Therefore, it is sufficient to employ inverse kinem atics only fo r the reference position $X_I = X_D - X_F$ defined in the Cartesian space.

4.2 Modified Admittance control

Similar to the Im pedance C ontrol m odifications, inne r pos ition loop o f the A dmittance Control scheme is m odified to m ake the nece ssary comparisons in the joint space and not in the Cartesian space. The m odified version of the A dmittance Control s cheme is presented in Figure 5.

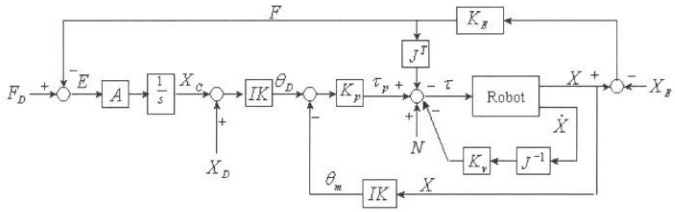

Fig.5. Modified Admittance control scheme

Position f eedback of the end-ef fector is ch anged to jo int position f eedback by in verse kinematics " IK " in the m odified schem e as it was the case in Im pedance Control

modifications. In a real application, it is also sufficient to employ inverse kinematics only for the reference position $X_{ref} = X_C + X_D$ defined in the Cartesian space.

4.2 Modified Hybrid Position/Force control

Hybrid control sch eme is also m odified to make the n ecessary com parisons in th e joint space and not in the Cartes ian s pace as sho wn in Figu re 6. Again , " IK " in th e f igure represents Inverse Kinematics.

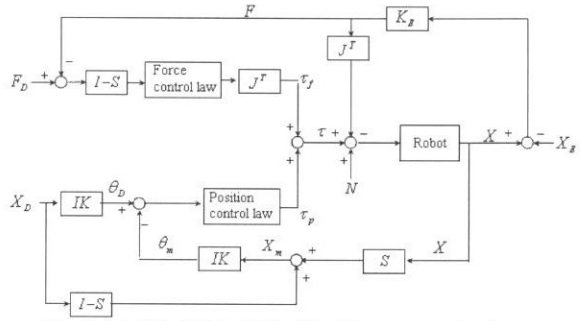

Fig.6. Modified Hybrid Position/Force control scheme

This modified version of the Hybrid Cont rol does not use the sele ction matrix, " S " after the comparison is made in the Cartesian Space for the position control subspace. The selection matrix is used to take the measured positions along the directions to be position controlled as they are and m odify the m easured position along the direction to be force controlled to the desired position along that dire ction. This m akes the positio n error alon g the direc tion to be force controlled equal to zero, which means that the controller working in the position control subspace will not try to monitor the position along the force control direction.

After these modifications on the measured position, " X ", the modified measured position, " X_m ", is transf ormed to th e Joint Spa ce to ca lculate the m odified m easured joint an gles, " θ_m ", using the inverse kinem atics equations. Desire d position vector is also transformed to the Joint Space us ing the inverse kinem atics equations. As a resu lt of this, th e comparison is made in the Joint Space and the outcome is fed into the position controller.

5. Simulation Test Results

The PUMA 560 6R manipulator, for which the system param eters are described in Bascuhadar's thesis [18], is used for num erical sim ulations. Point typ e of contact and the force sensor are consid ered to be at the end po int of the end-effector for th is study. A ll the simulations are carried out in Matlab © Simulink environm ent. The forward kinem atics and system dynamics are modeled using the Simmechanics module of Matlab©.

No surface or joint friction is m odeled for the simulations presented in this paper for th e sake of sim plicity. The contac t is assum ed to occur in such a way that only one degree of freedom is constrained by a flat surface normal to $\vec{u}_1^0$ (X) axis as illustrated in Figure 7.

The task to be accomplished for this simulation study is drawing a circle on a flat and rigid surface. The diam eter of the circle to be draw n for the Hybrid Control is 0.3 m eters and for the Admittance Control is 0.2 m eters. This is an arbitrary selection for the diameters with the

only restriction that the circles remain within the workspace of the manipulator. The link and joint parameters of the Puma 560 used in this work are given in Table 1.

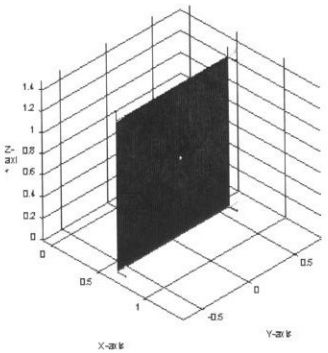

Fig.7. The task plane considered in the simulation examples

The manipulator is required to apply a 15 N pressing force while drawing the circles for the Admittance and Hybrid Controls. However, since the control scheme of Impedance control does not include a force demand input, the Impedance Control scheme tries to reduce the contact forces to zero as smoothly as possible. Figures 8, 9 and 10 show the circle drawn on $\vec{u}_2^0$ (Y) - $\vec{u}_3^0$ (Z) plane by the tip of the end-effector when the manipulator is controlled with the modified Impedance, Admittance and Hybrid control schemes, respectively.

Table 1. Link and Joint Parameters of PUMA 560 Manipulator

Joints	α_k (deg.)	s_k (mm.)	a_k (mm.)	θ_k (deg.)
1 -	90°	0 0		θ_1
2 0		81.5	300	θ_2
3 9	0° 0		0	θ_3
4 -	90° 30	4.5	0	θ_4
5 9	0° 0		0	θ_5
6 0		0	0	θ_6

$(Ms^2 + Ds + K)^{-1}$ term in Impedance Control is considered as an second order system and the parameters of this term are determined within this assumption. ζ is selected as 0.8 and ω_n is selected as 15, 6 rad/s respectively. Different parameters are tried for the force-controlled outer loop of the Admittance Control and the force-controlled sub-space of the Hybrid Control. Suitable set of parameters lead to the force plots shown in Figures 11, 12 and 13. The corresponding parameters are presented in the legends of these plots. PID control is used for the force-controlled outer loop of the Admittance Control to form the A matrix as in equation (9). PI control is preferred for the force-controlled sub-space of the Hybrid Control.

As for the mobility directions, PD parameters for the position-controlled inner loop of the Impedance Control, Admittance Control and the position-controlled sub-space of the Hybrid Control are selected using the method explained in the thesis of Dede [5], which is also briefly

outlined here: Since the nonlinear feed-forward compensation term " N " cancels out the Coriolis, centrifugal and gravitational forces, the reduced equation of motion ($M\ddot{\theta} = \tau^* + \tau'$) resembles to that of a double-integrator plant with control and disturbance inputs τ^* and τ'. Utilizing this fact, the control input is generated with a PD action as

$$\tau^* = K_p(\theta_r - \theta) + K_d(\dot{\theta}_r - \dot{\theta}) \qquad (14)$$

and the parameters K_p and K_v are determined as follows:

$$K_v = 2\zeta\omega_n M', \qquad (15)$$

$$K_p = \omega_n^2 M'. \quad (16)$$

Here, for sake of simplicity, M' is taken as the diagonal portion of the mass matrix M. The damping ratio ζ is selected as 0.8 and the natural frequency ω_n is selected as 50 rad/s, which happens to be a reasonable value determined after few trials. The position control performance of the manipulator in tracking the required circular paths can also be depicted in Figures 8, 9 and 10 for the Impedance, Admittance and the Hybrid control schemes.

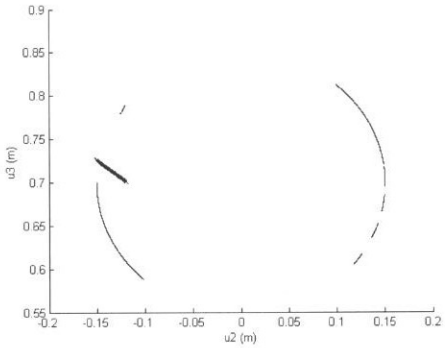

Fig.8. Circle drawn on the task plane by the manipulator using Impedance Control

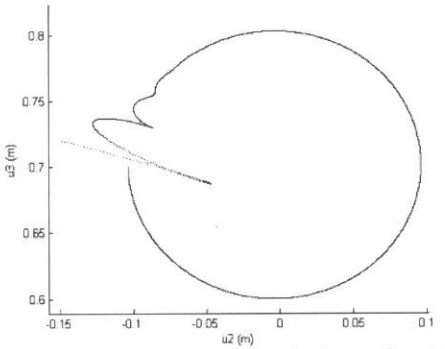

Fig.9. Circle drawn on the task plane by the manipulator using Admittance Control

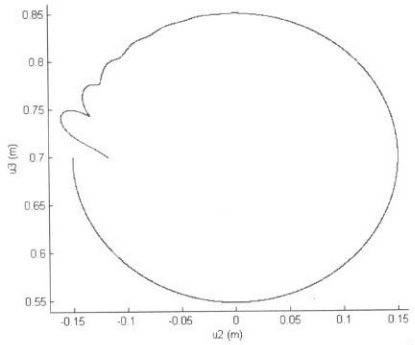

Fig.10. Circle drawn on the task plane by the manipulator using Hybrid Control

It can be clearly s een in Figure 8 that th e m anipulator is on and off contact with the surface. The line has red uced thickness indicating the decrease in contact forces as a result of the Im pedance Control schem e trying to redu ce the im pact force to zero. As it can be observed from Figures 8, 9 and 10, there are ove rshoots and oscillations at the beginning of the operation in both control schem es. This is due to the disorienta tion of the en d-effector from the desired one at the beginning and trying to catch up with the desired orientation as the operation continues. The initial overshoots and oscillations can be eliminated to a large extent by starting the operation at th e correct orientation or by giving the m anipulator some tim e to correct its orientation before st arting the task. Another fact to be pointed out is that the operation does not necessarily start at contact with the surface and it takes varying amount of time for each control s cheme to drive the end-eff ector into contact. Mo reover, for the Hybrid Control app lication, it is required to sw itch to a pure position controlle r until the contac t is established.

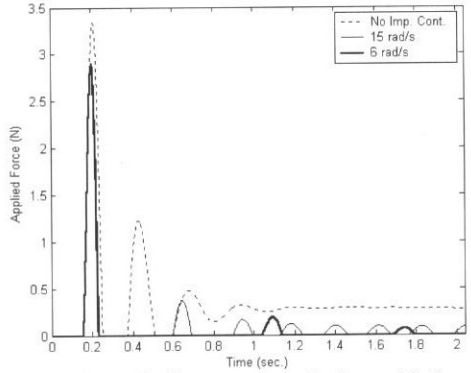

Fig.11. Force applied by the end-effector to the task plane with the modified Impedance Control scheme

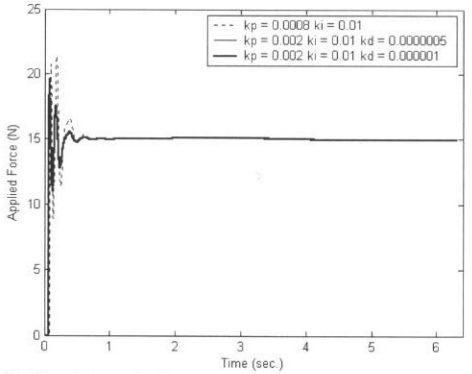

Fig.12. Force applied by the end-effector to the task plane with the modified Admittance Control scheme

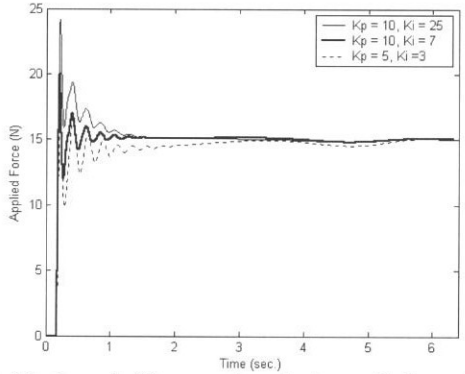

Fig.13. Force applied by the end-effector to the task plane with the modified Hybrid Control scheme

6. Conclusions

In the proposed m odifications to the position/ force contro l schem es investig ated in th is paper, the position errors in the joint space are determ ined exactly by using the inverse kinematic s olution ins tead of dete rmining th em approxim ately by m eans of the inverse Jacobian m atrix as in the cus tomary schem es. Therefore, it b ecomes possib le with th e modified schem es to elim inate the instabilit y problem that m ay occur in the cu stomary schemes when the initial errors are large or when the end-effector is distracted largely from its desired course by a heavy disturbance. One s ource of disturbance can be the communication delays or losses that teleop eration system s m ay experience. In fact, these types of position/force controllers are widely used as teleoperation subsystem controllers.

The overshoots and oscillations that are observ ed in the sim ulations during the tran sient phase of both control schem es may be reduced, even if the starting orientation of the end-effector is not as desired, by using m ore ela borately determ ined control gains that contain scheduling with error and/or time. Such an improvement can be studied as an extension of this work. Other item s that m ay be considered in an extended study includ e surfaces o ther than

planar ones, edge and surface contacts in addition to point contacts, and contacts with friction involving stick/slip motions.

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Functional Safety Assessment for the Assistive Robot FRIEND[1]

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Abstract

This paper proposes methods for the safe development of the assistive robot FRIEND. The approach started by the hazard identification via the well known system engineering methods. These methods have been used in avionics and nuclear power plants, and can be applied to the safety critical service robots as well; they reveal all potential hazards at the system and component level during design stages. In this context, the systematic bottom-up (Hazard and Operability Study: HAZOP, Failure mode and Effect Analysis: FMEA) and top-down (Fault Tree Analysis: FTA) hazard identification methods are used to determine safety requirements. For this purpose the software tool APIS IQ-RM Pro[2] (hereafter referred to as APIS) is used to systematically document the results, also to facilitate version control inside the development group. The tool supports both the FMEA and FTA by a systematic stepwise procedure. The result of hazard identification leads to the safety requirements that determine the safety functions needed to mitigate potential critical hazards in the system.

1. Introduction

Up until now, most service robot development has concentrated primarily on the realization of an operating system with less attention given to safety issues. In the past, some researches have been done in safe development of robot components. The development of light weight robot arms with reduced impact upon contact is a good example in this field as discussed in [1] and [5]. The improvement has been done on mechanical parts using smooth and non-sharp structures. Control strategies have also been modified to reduce inertia and contact impact. However, service robots are often used in a wide range of applications and therefore building an overall safe service robot system is not only achieved by reducing impact upon contact with the user. The safety measurements are system related and depend on the operating tasks. A robot arm, equipped with tactile sensors for impact reduction, might still be unsafe. For example consider a servant robot, if the reaction to the over speed movement of the arm is too slow, or if a fast reaction were to cause a heavy object to slip from the robots hand, the robot would not be safe. Therefore the functional safety is very important and must be considered during the design process. However, the researches on functional and overall safety of the service robot systems are still rare.
Here to assure coverage for all hazards in complex service robot like FRIEND, both systematic bottom-up and top-down hazard analysis methods is carried out. The systematic bottom-up hazard analysis provides answers to the question " What consequences does a given hazard

[1] FRIEND is an assistive service robot under development at IAT institute, university of Bremen, more details are given in [2,4]
[2] APIS IQ-RM Pro is a commercial tool for hazard identification and is available free for education purposes [2].