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Model Reference Adaptive Control for Robotic Manipulation with Kalman Active Observers

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1. Introduction

Nowadays, the presence of robotics in human-oriented applications demands control paradigms to face partly known, unstructured and time-varying environments. Contact tasks and compliant motion strategies cannot be neglected in this scenario, enabling safe, rewarding and pleasant interactions. Force control, in its various forms, requires special attention, since the task constraints can change abruptly (e.g. free-space to contact transitions) entailing wide variations in system parameters. Modeling contact/non-contact states and designing appropriate controllers is yet an open problem, even though several control solutions have been proposed along the years. Two main directions can be followed, depending on the presence of force sensors. The perception of forces allows explicit force control (e.g. hybrid position/force control) to manage the interaction imposed by the environment, which is in general more accurate than implicit force control schemes (e.g. impedance control) that do not require force sensing. A major problem of force control design is the robustness to disturbances present in the robotic setup. In this context, disturbances include not only system and measurement noises but also parameter mismatches, nonlinear effects, discretization errors, couplings and so on. If the robot is interacting with unknown objects, "rigid" model based approaches are seldom efficient and the quality of interaction can be seriously deteriorated. Model reference adaptive control (MRAC) schemes can have an important role, imposing a desired closed loop behavior to the real plant in spite of modeling errors.

This chapter introduces the Active Observer (AOB) algorithm for robotic manipulation. The AOB reformulates the classical Kalman filter (CKF) to accomplish MRAC based on: 1) A desired closed loop system. 2) An extra equation to estimate an equivalent disturbance referred to the system input. An active state is introduced to compensate unmodeled terms, providing compensation actions. 3) Stochastic design of the Kalman matrices. In the AOB, MRAC is tuned by stochastic parameters and not by control parameters, which is not the approach of classical MRAC techniques. Robotic experiments will be presented, highlighting merits of the approach. The chapter is organized as follows: After the related work described in Section 3, the AOB concept is analyzed in Sections 4, 5 and 6, where the general algorithm and main design issues are addressed. Section 7 describes robotic

experiments. The execution of the peg-in-hole task with tight clearance is discussed. Section 8 concludes the chapter.

2. Keywords

Kalman Filter, State Space Control, Stochastic Estimation, Observers, Disturbances, Robot Force Control.

3. Related Work

Disturbance sources including external disturbances (e.g. applied external forces) and internal disturbances (e.g. higher order dynamics, nonlinearities and noise) are always present in complex control systems, having a key role in system performance. A great variety of methods and techniques have been proposed to deal with disturbances. De Schutter [Schutter, 1988] has proposed an extended deterministic observer to estimate the motion parameters of a moving object in a force control task. In [Chen et al., 2000], model uncertainties, nonlinearities and external disturbances are merged to one term and then compensated with a nonlinear disturbance observer based on the variable structure system theory. Several drawbacks of previous methods are also pointed out in [Chen et al., 2000]. The problem of disturbance decoupling is classical and occupies a central role in modern control theory. Many control problems including robust control, decentralized control and model reference control can be recast as an almost disturbance decoupling problem. The literature is very extensive on this topic. To tackle the disturbance decoupling problem, PID-based techniques [Estrada & Malabre, 1999], state feedback [Chu & Mehrmann, 2000] geometric concepts [Commault et al., 1997], tracking schemes [Chen et al., 2002] and observer techniques [Oda, 2001] have been proposed among others. In [Petersen et al., 2000], linear quadratic Gaussian (LQG) techniques are applied to uncertain systems described by a nominal system driven by a stochastic process. Safanov and Athans [Safanov & Athans, 1977] proofed how the multi-variable LQG design can satisfy constraints requiring a system to be robust against variations in its open loop dynamics. However, LQG techniques have no guaranteed stability margins [Doyle, 1978], hence Doyle and Stein have used fictitious noise adjustment to improve relative stability [Doyle & Stein, 1979].

In the AOB, the disturbance estimation is modeled as an auto-regressive (AR) process with fixed parameters driven by a random source. This process represents stochastic evolutions. The AOB provides a methodology to achieve model-reference adaptive control through extra states and stochastic design in the framework of Kalman filters.

It has been applied in several robotic applications, such as autonomous compliant motion of robotic manipulators [Cortês et al., 2000], [Cortês et al., 2001], [Park et al., 2004], haptic manipulation [Cortês et al., 2006], humanoids [Park & Khatib, 2005], and mobile systems [Coelho & Nunes, 2005], [Bajcinca et al., 2005], [Cortês & Bajcinca, 2004], [Maia et al., 2003].

4. AOB Structure

Given a discretized system with equations

$$x_{r,k} = \Phi_r x_{r,k-1} + \Gamma_r u_{k-1} + \xi_{x_{r,k}} \quad (1)$$

and

$$y_k = C_r x_{r,k} + \eta_k, \quad (2)$$

an observer of the state $x_{r,k}$, $\hat{x}_{r,k}$, can be written as

$$\hat{x}_{r,k} = \Phi_{r,n} \hat{x}_{r,k-1} + \Gamma_{r,n} u_{k-1} + K_k [y_k - C_r (\Phi_{r,n} \hat{x}_{r,k-1} + \Gamma_{r,n} u_{k-1})], \quad (3)$$

where $\Phi_{r,n}$ and $\Gamma_{r,n}$ are respectively the nominal state transition and command matrices (i.e., the ones used in the design). Φ_r and Γ_r are the real matrices. $\xi_{x_{r,k}}$ and η_k are Gaussian random variables associated to the system and measures, respectively, having a key role in the AOB design. Defining the estimation error as

$$e_{r,k} = x_{r,k} - \hat{x}_{r,k}, \quad (4)$$

and considering ideal conditions (i.e., the nominal matrices are equal to the real ones and $\xi_{x_{r,k}}$ and η_k are zero), $e_{r,k}$ can be computed from (1) and (3). Its value is

$$e_{r,k} = (\Phi_r - K_k C_r \Phi_r) e_{r,k-1}. \quad (5)$$

The error dynamics given by the eigenvalues of $(\Phi_r - K_k C_r \Phi_r)$ is function of the K_k gain. The Kalman observer computes the best K_k in a straightforward way, minimizing the mean square error of the state estimate due to the random sources $\xi_{x_{r,k}}$ and η_k . When there are unmodeled terms, (5) needs to be changed. A deterministic description of $e_{r,k}$ is difficult, particularly when unknown modeling errors exist. Hence, a stochastic approach is attempted to describe it. If state feedback from the observer is used to control the system, p_k enters as an additional input

$$p_k = L_r e_{r,k}, \quad (6)$$

where L_r is the state feedback gain. A state space equation should be found to characterize this undesired input, leading the system to an extended state representation. Figure 1 shows the AOB.

To be able to track functions with unknown dynamics, a stochastic equation is used to describe p_k

$$p_k - p_{k-1} = \xi_{p_k}, \quad (7)$$

in which ξ_{p_k} is a zero-mean Gaussian random variable¹. Equation (7) says that the first derivative (or first-order evolution) of p_k is randomly distributed. Defining ${}^N \xi_{p_k}$ as the N^{th} -order evolution of ξ_{p_k} (or the $(N+1)^{th}$ order evolution of p_k),

$${}^N \xi_{p_k} = {}^{N-1} \xi_{p_k} - {}^{N-1} \xi_{p_{k-1}}, \quad \text{with } {}^0 \xi_{p_k} = \xi_{p_k}, \quad (8)$$

the general form of (7) is

¹ The mathematical notation along the paper is for single input systems. For multiple input systems, p_k , in (7) is a column vector with dimension equal to the number of inputs.

the discrete time system

$$\begin{bmatrix} x'_k \\ u_{k-d} \\ \vdots \\ u_{k-2} \\ u_{k-1} \end{bmatrix} = \begin{bmatrix} \Phi_1 & \Gamma_1 & \Gamma_0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} x'_{k-1} \\ u_{k-d-1} \\ \vdots \\ u_{k-3} \\ u_{k-2} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} u_{k-1} \quad (12)$$

and

$$y_k = C_r x_{r,k} \quad (13)$$

is obtained Φ_1 , Γ_0 and Γ_1 are given by (14) to (16), respectively [Aström & Wittenmark, 1997].

$$\Phi_1 = e^{Ah} = \phi(h), \quad (14)$$

$$\Gamma_0 = \int_0^{h-\tau'} \phi(\lambda) d\lambda B \quad (15)$$

and

$$\Gamma_1 = \phi(h - \tau') \int_0^{\tau'} \phi(\lambda) d\lambda B. \quad (16)$$

The state $x_{r,k}$ is

$$x_{r,k} = \begin{bmatrix} x'_k & u_{k-d} & \cdots & u_{k-2} & u_{k-1} \end{bmatrix}^T, \quad (17)$$

in which x'_k is the system state considering no dead-time. Therefore, the τ of (6.10) increases the system order.

5.2 AOB-1 Algorithm

From Figure 1 and knowing (1) and (7), the augmented state space representation (open loop)³ is

$$\begin{bmatrix} x_{r,k} \\ p_k \end{bmatrix} = \begin{bmatrix} \Phi_r & \Gamma_r \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{r,k-1} \\ p_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_r \\ 0 \end{bmatrix} u'_{k-1} + \begin{bmatrix} \xi_{x_{r,k}} \\ \xi_{p_k} \end{bmatrix} \quad (18)$$

where

$$u'_{k-1} = r_{k-1} - \begin{bmatrix} L_r & 1 \end{bmatrix} \begin{bmatrix} x_{r,k-1} \\ \hat{p}_{k-1} \end{bmatrix}, \quad (19)$$

³ In this context, open loop means that the state transition matrix does not consider the influence of state feedback.

$$\Phi_r = \begin{bmatrix} \Phi_1 & \Gamma_1 & \Gamma_0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \quad (20)$$

and

$$\Gamma_r = [0 \ 0 \ \cdots \ 0 \ 1]^T. \quad (21)$$

L_r is obtained by any control technique applied to (12) to achieve a desired closed loop behavior. The measurement equation is

$$y_k = C \begin{bmatrix} x_{r,k} \\ p_k \end{bmatrix} + \eta_k, \quad (22)$$

with⁴

$$C = [C_r \ 0]. \quad (23)$$

The desired closed loop system appears when $\hat{p}_k = p_k$ i.e.,

$$\begin{bmatrix} x_{r,k} \\ p_k \end{bmatrix} = \begin{bmatrix} \Phi_r - \Gamma_r L_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{r,k-1} \\ p_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_r \\ 0 \end{bmatrix} r_{k-1} + \begin{bmatrix} \xi_{x_{r,k}} \\ \xi_{p_k} \end{bmatrix}. \quad (24)$$

The state $x_{r,k}$ in (24) is accurate if most of the modeling errors are merged to p_k . Hence, $\xi_{x_{r,k}}$ should be small compared to ξ_{p_k} . The state estimation⁵ must consider not only the influence of the uncertainty $\xi_{x_{r,k}}$, but also the deterministic term due to the reference input, the extended state representation and the desired closed loop response. It is given by⁶

$$\begin{bmatrix} \hat{x}_{r,k} \\ \hat{p}_k \end{bmatrix} = \begin{bmatrix} \Phi_{r,n} - \Gamma_{r,n} L_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x}_{r,k-1} \\ \hat{p}_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_{r,n} \\ 0 \end{bmatrix} r_{k-1} + K_k \left\{ y_k - C \left(\begin{bmatrix} \Phi_{r,n} - \Gamma_{r,n} L_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x}_{r,k-1} \\ \hat{p}_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_{r,n} \\ 0 \end{bmatrix} r_{k-1} \right) \right\}. \quad (25)$$

K_k is

$$K_k = P_{1k} C^T [C P_{1k} C^T + R_k]^{-1}, \quad (26)$$

and

$$P_{1k} = \Phi_n P_{k-1} \Phi_n^T + Q_k, \quad (27)$$

⁴ The form of C is maintained for the AOB-N, since the augmented states that describe p_k are not measured.

⁵ The CKF algorithm can be seen in [Bozic, 1979].

⁶ $\Phi_{r,n}$ and $\Gamma_{r,n}$ represent the nominal values of $\Phi_{r,n}$ and $\Gamma_{r,n}$, respectively.

with

$$P_k = P_{1k} - K_k C P_{1k}. \quad (28)$$

Φ_n is the augmented open loop matrix used in the design,

$$\Phi_n = \begin{bmatrix} \Phi_{r,n} & \Gamma_{r,n} \\ 0 & 1 \end{bmatrix}. \quad (29)$$

Q_k is the system noise matrix,⁷

$$Q_k = \begin{bmatrix} Q_{x_{r,k}} & 0 \\ 0 & Q_{p_k} \end{bmatrix}. \quad (30)$$

R_k is the measurement noise matrix, $R_k = E \{ \eta_k \eta_k^T \}$. P_k is the mean square error matrix. It should be pointed out that P_{1k} given by (6.27) uses Φ_n . More details can be seen in [Cortês, 2007].

6. AOB-N Design

The AOB-N is discussed in this section enabling stronger nonlinearities to be compensated by \hat{p}_k . Section 6.6.1 presents the AOB-N algorithm and Section 6.2 discusses the stochastic structure of AOB matrices.

6.1 AOB-N Algorithm

The AOB-1 algorithm has to be slightly changed for the AOB-N. Only the equation of the active state changes, entailing minor modifications in the overall AOB design. Equation (9) has the following state space representation:

$$\begin{bmatrix} p_{k-(N-1)} \\ p_{k-(N-2)} \\ \vdots \\ p_{k-1} \\ p_k \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ a_N & a_{N-1} & a_{N-2} & \cdots & a_1 \end{bmatrix} \begin{bmatrix} p_{k-N} \\ p_{k-(N-1)} \\ \vdots \\ p_{k-2} \\ p_{k-1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ {}^{N-1}\xi_{p_k} \end{bmatrix}, \quad \text{with } a_i = (-1)^{i+1} \frac{N!}{i!(N-i)!}, \quad i = 1, \dots, N. \quad (31)$$

In compact form, (31) is represented by

$${}^N p_k = \Phi_{2,2} {}^N p_{k-1} + \xi_{N p_k}. \quad (32)$$

⁷ Further analysis of the Q_k matrix is given in Section 6.2.

Equation (18) is now re-written as

$$\begin{bmatrix} x_{r,k} \\ {}^N p_k \end{bmatrix} = \begin{bmatrix} \Phi_r & \Phi_{1,2} \\ 0 & \Phi_{2,2} \end{bmatrix} \begin{bmatrix} x_{r,k-1} \\ {}^N p_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_r \\ 0 \end{bmatrix} u'_{k-1} + \begin{bmatrix} \xi_{x_{r,k}} \\ \xi_{{}^N p_k} \end{bmatrix}, \quad (33)$$

where

$${}^N p_k = [p_{k-(N-1)} \quad p_{k-(N-2)} \quad \cdots \quad p_{k-1} \quad p_k]^T. \quad (34)$$

$\Phi_{2,2}$ is the state transition matrix of (31),

$$\Phi_{1,2} = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} \quad (35)$$

and

$$\xi_{{}^N p_k} = [0 \quad 0 \quad \cdots \quad 0 \quad {}^{N-1}\xi_{p_k}]^T. \quad (36)$$

The desired closed loop of (24) is changed to

$$\begin{bmatrix} x_{r,k} \\ {}^N p_k \end{bmatrix} = \begin{bmatrix} \Phi_L & 0 \\ 0 & \Phi_{2,2} \end{bmatrix} \begin{bmatrix} x_{r,k-1} \\ {}^N p_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_r \\ 0 \end{bmatrix} r_{k-1} + \begin{bmatrix} \xi_{x_{r,k}} \\ \xi_{{}^N p_k} \end{bmatrix}, \quad (37)$$

with

$$\Phi_L = \begin{bmatrix} \Phi_1 & \Gamma_1 & \Gamma_0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ -L_1 & -L_2 & -L_3 & \cdots & -L_M \end{bmatrix}. \quad (38)$$

The L_r components (L_1, \dots, L_M) can be obtained by Ackermann's formula, i.e.,

$$L_r = [0 \quad \cdots \quad 0 \quad 1] W_c^{-1} P(\Phi_r). \quad (39)$$

W_c is the reachability matrix

$$W_c = [\Gamma_r \quad \Phi_r \Gamma_r \quad \cdots \quad \Phi_r^{M-1} \Gamma_r], \quad (40)$$

and $P(\Phi_r)$ is the desired characteristic polynomial. The state estimation is⁸

⁸ $\Phi_{L,n}$ is the nominal value of Φ_L

$$\begin{bmatrix} \hat{x}_{r,k} \\ {}^N\hat{p}_k \end{bmatrix} = \begin{bmatrix} \Phi_{L,n} & 0 \\ 0 & \Phi_{2,2} \end{bmatrix} \begin{bmatrix} \hat{x}_{r,k-1} \\ {}^N\hat{p}_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_{r,n} \\ 0 \end{bmatrix} r_{k-1} + K_k \left\{ y_k - C \left(\begin{bmatrix} \Phi_{L,n} & 0 \\ 0 & \Phi_{2,2} \end{bmatrix} \begin{bmatrix} \hat{x}_{r,k-1} \\ {}^N\hat{p}_{k-1} \end{bmatrix} + \begin{bmatrix} \Gamma_{r,n} \\ 0 \end{bmatrix} r_{k-1} \right) \right\}. \quad (41)$$

K_k is given by (26) to (28), with

$$\Phi_n = \begin{bmatrix} \Phi_{r,n} & \Phi_{1,2} \\ 0 & \Phi_{2,2} \end{bmatrix}. \quad (42)$$

The state feedback gain L is

$$L = \begin{bmatrix} L_r & L_{Np_k} \end{bmatrix}, \quad (43)$$

with

$$L_{Np_k} = \begin{bmatrix} 0 & \cdots & 0 & 1 \end{bmatrix}. \quad (44)$$

6.2 AOB-N Matrices

R_k is function of sensor characteristics. The form of Q_k is

$$Q_k = \begin{bmatrix} Q_{x_{r,k}} & 0 \\ 0 & Q_{Np_k} \end{bmatrix}. \quad (45)$$

$Q_{x_{r,k}}$ is a diagonal matrix. The uncertainty associated with $x_{r,k}$ is low since all system disturbances should be compensated with Np_k . Hence, $Q_{x_{r,k}}$ should have low values compared to Q_{Np_k} , which is defined as

$$Q_{Np_k} = E \left\{ \xi_{Np_k} \cdot \xi_{Np_k}^T \right\}. \quad (46)$$

From (36),

$$Q_{Np_k} = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{N-1}^2 \xi_{p_k} \end{bmatrix}. \quad (47)$$

$\sigma_{N-1}^2 \xi_{p_k}$ represents the variance of the N^{th} derivative of p_k , and is related with $\sigma_{\xi_{p_k}}^2$. Hence, the design can be done for $\sigma_{\xi_{p_k}}^2$ (see [Cortezão, 2007]).

6.3 AOB Estimation Strategies

An important property of the Kalman gain is introduced in Proposition 1, enabling to define different estimation strategies.

Proposition 1 *The Kalman gain K_k obtained from (26) to (28) does not have a unique solution.*

Proof: Using (27) and (28), the matrix P_k can be written in a recursive way as

$$P_k = (I - K_k C_a)(\Phi_a P_{k-1} \Phi_a^T + Q_k). \quad (48)$$

Let's consider one solution

$$(Q_k, R_k, P_0) \rightarrow (K_k, P_k). \quad (49)$$

Another candidate solution

$$(Q'_k, R'_k, P'_0) \rightarrow (K_k, P'_k) \quad (50)$$

should be found, giving the same K_k values. If

$$Q'_k = \alpha Q_k, \quad (51)$$

in which α is a scalar⁹, (48) is satisfied if

$$P'_k = \alpha P_k \text{ and } P'_{k-1} = \alpha P_{k-1}. \quad (52)$$

Hence, from (27), (51) and (52),

$$P'_{1k} = \alpha P_{1k}. \quad (53)$$

From (26), the new Kalman gain K'_k is

$$\begin{aligned} K'_k &= P'_{1k} C_a^T [C_a P'_{1k} C_a^T + R'_k]^{-1} \\ &= \alpha P_{1k} C_a^T [C_a \alpha P_{1k} C_a^T + R'_k]^{-1}. \end{aligned} \quad (54)$$

To accomplish $K'_k = K_k$, it is necessary that $R'_k = \alpha R_k$. The candidate solution exists and is

$$(Q'_k = \alpha Q_k, R'_k = \alpha R_k, P'_0 = \alpha P_0) \rightarrow (K_k, P'_k = \alpha P_k). \quad (55)$$

Corollary 1 *What defines the Kalman gain, or the estimation strategy, are only the relations between the Q_k values, the R_k values, and both Q_k and R_k values.*

Proof: Similar to Proposition 1. •

In the AOB, the relations between the Q_k values are straightforward. The estimation strategy is thus based on the relation between Q_k and R_k . If model accuracy is very good compared with measure accuracy, a model based approach (MBA) is followed. The estimation \hat{x}_k given by (6.41) is mainly based on the model, giving little importance to measures. The Kalman gain has low values. On the other hand, if the measures are very accurate with respect to the model, a sensor based approach (SBA) is followed. The estimates are very sensitive to measures. The Kalman gain has high values. The hybrid based approach (HBA) is the general form of the AOB and establishes a trade-off between the SBA and MBA, i.e. it balances the estimates based on sensory and model information. To keep the same strategy as the AOB order changes, some adjustments in Q_k or R_k may be necessary, since the extended system matrix Φ_a that affects K_k changes.

⁹ Physically, it makes no sense a negative value of α .

Eliminating the active state and redesigning Q (with new values) gives the CKF. In this situation, the Q design is not straightforward. Nevertheless, the relation between Q and R defines the control strategy.

For complex control tasks (e.g. compliant motion control), switching between AOB and CKF may appear dynamically as a function of the task state.

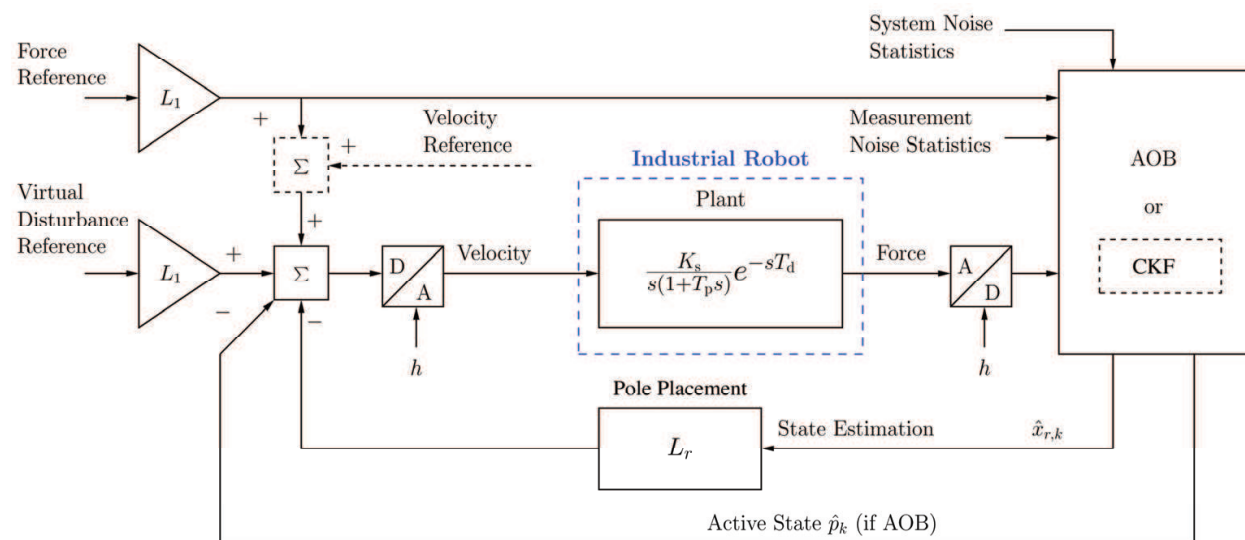


Figure 2. Global control scheme for each force/velocity dimension. K_s is the system stiffness. T_p is the position response time constant, and T_d is the system time delay due to the signal processing of the cascade controller

7. Experiments

If a manipulator is working in free space, position or velocity control of the end-effector is sufficient. For constrained motion, specialized control techniques have to be applied to cope with natural and artificial constraints. The experiments reported in this section apply AOBs to design a compliant motion controller (CMC) for the peg-in-hole task, guaranteeing model reinforcement in critical directions.

7.1 Peg-in-Hole Task

The robotic peg-in-hole insertion is one of the most studied assembly tasks. This longstanding problem has had many different solutions along the years. If the peg-hole clearance is big, position controlled robots can perform the task relatively easy. Otherwise, force control is necessary. The insertion requires position and angular constrained motion, which is a common situation in automation tasks. Several authors have tackled the peg-in-hole problem. Yoshimi and Allen [Yoshimi & Allen, 1994] performed the peg-in-hole alignment using uncalibrated cameras. Broenink and Tiernego [Broenink & Tiernego, 1996] applied impedance control methods to peg-in-hole assembly. Itabashi and co-authors [Itabashi et al., 1998] modeled the impedance parameters of a human based peg-in-hole insertion with hidden Markov models to perform a robotic peg-in-hole task. In [Morel et al., 1998], the peg-in-hole task is done combining vision and force control, and in [Kim et al., 2000], stiffness analysis is made for peg-in/out-hole tasks, showing the importance of the

compliance center location. Newman and co-authors [Newman et al., 2001] used a feature based technique to interpret sensory data, applying it to the peg-in-hole task.

Parameter	Value
T_p	0.032 [s]
T_d	0.040 [s]
h	0.008 [s]
K_w	3 [N/mm] (x lin.) 3 [N/mm] (y lin.) 20 [N/mm] (z lin.) 100 [Nm/rad] (x rot.) 100 [Nm/rad] (y rot.)

Table 1. Technology parameters of the Manutec R2 robot. Stiffness data

In our setup, the robotic peg-in-hole task is performed with an AOB based CMC. Figure 6.2 represents the CMC for each force dimension. The main goal is the human-robot skill transfer of the peg-in-hole task. The task is previously performed by a human, where the forces, torques and velocities of the peg are recorded as a function of its pose, using a teaching device. The robot should be able to perform the same task in a robust way after the skill transfer [Cortesão et al., 2004]. The CMC is an important part of the system, since it tries to accomplish a desired compliant motion for a given geometric information. This CMC may change on-line between full AOB, CKF or "pure" state feedback, based on the task state. If velocity signals are dominant, the CKF should be used since the full AOB annihilates any external inputs. If force signals are dominant, the full AOB is a good choice. Hence, the CMC can easily handle two reference inputs, f_d (force) and v_d (velocity). The natural constraints imply complementarity of the reference signals. When f_d is different than zero v_d is almost zero and vice-versa. In the sequel, the performance of the 6 DOF peg-in-hole task is analyzed with the AOB and CKF in the loop.

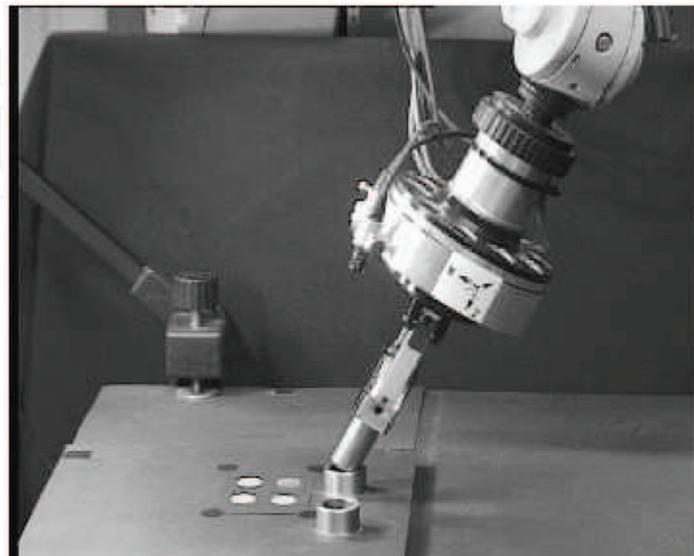
7.2 Experimental Setup

Experimental tests have been done in a robotic testbed at DLR (German Aerospace Center). The main components of this system are:

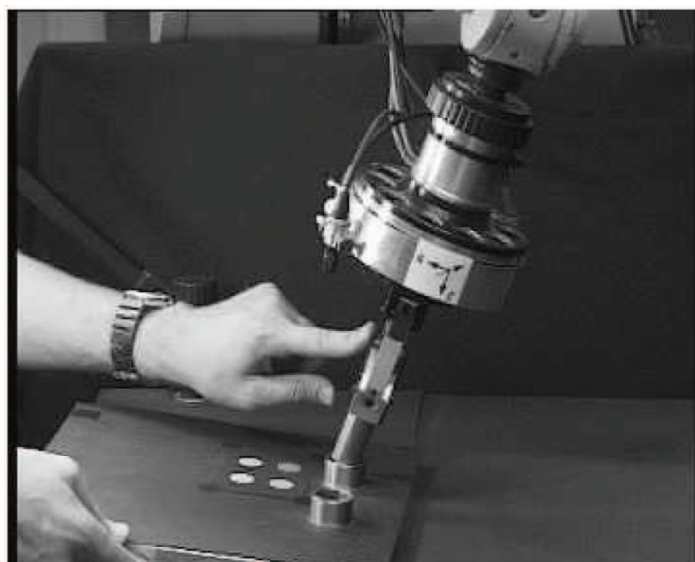
- A Manutec R2 industrial robot with a Cartesian position interface running at 8 [ms] and an input dead-time of 5 samples, equivalent to 40 [ms].
- A DLR end-effector, which consists of a compliant force/torque sensor providing force/torque measurements every 8 [ms]. The technology data of the robot and the force sensor stiffness are summarized in Table 6.1. The manipulator compliance is lumped in the force sensor.
- A multi-processor host computer running UNIX, enabling to compute the controller at each time step.
- Two cameras for stereo vision are mounted on the end-effector. A pneumatic gripper holds a steel peg of 30 [mm] length and of 23 [mm] diameter. The peg-hole has a clearance of 50 [μm], which corresponds to a tolerance with ISO quality 9. The hole is

chamferless. The environment is very stiff ($K_s \approx K_w$). Vision and pose sense belong to the data fusion architecture (see [Cortês et al., 2004]).

- A picture of the experimental setup is depicted in Figure 3. Figure 3.a represents the peg-in-hole task with a three point contact. Figure 3.b shows the task execution with human interference.



(a)



(b)

Figure 3. Experimental setup, (a) Manutec R2 robot ready to perform the peg-in-hole task, (b) Human interaction during the peg-in-hole task

7.3 AOB Matrices

This section discusses the AOB design for the CMC controller.

System Plant Matrices

For each DOF, the position response of the Manutec R2 robot is

$$G_p(s) = \frac{1}{1 + T_p s} e^{-sT_d}. \quad (56)$$

Inserting the system stiffness K_s , the system plant can be written as

$$G(s) = \frac{k_1}{s(s + p_1)} e^{-st_d}, \quad (57)$$

with

$$k_1 = K_s/T_p, \quad p_1 = 1/T_p \quad \text{and} \quad t_d = T_d. \quad (58)$$

Its equivalent temporal representation is

$$\ddot{y} + p_1 \dot{y} = k_1 u(t - t_d), \quad (59)$$

where y is the plant output (force) and u is the plant input (velocity). Defining the state variables as

$$x_1 = y \quad \text{and} \quad x_2 = \dot{y}, \quad (60)$$

the state space description of (59) is given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -p_1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ k_1 \end{bmatrix} u(t - t_d). \quad (61)$$

Physically, x_1 represents the force at the robot's end effector and x_2 is the force derivative. Knowing (61), the AOB design described in Sections 5 and 6 can be applied in straightforward way.

Stochastic Matrices

For the first dimension f_x ,

$$Q_k(f_x) = \begin{bmatrix} 10^{-12} & \dots & 0 & 0 \\ 0 & \dots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & 10^{-12} & 0 \\ 0 & \dots & 0 & 10^{-5} \end{bmatrix}, \quad (62)$$

and

$$P_0(f_x) = \begin{bmatrix} 10^{-4} & 0 & \dots & 0 & 0 \\ 0 & 10^{-4} & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & 10^{-4} & 0 \\ 0 & 0 & \dots & 0 & 10^{-4} \end{bmatrix}. \quad (63)$$

The value of R_k was obtained experimentally. It is given by

$$R_k(f_x) = 2.1 \times 10^{-2}. \quad (64)$$

For the second dimension f_y , Q_k is

$$Q_k(f_y) = Q_k(f_x)R_k(f_y)/R_k(f_x),$$

(65)

$$P_0(f_y) = P_0(f_x)R_k(f_y)/R_k(f_x),$$

(66)

with

$$R_k(f_y) = 7.4 \times 10^{-4}.$$

(67)

Analogous equations are obtained for the other force/torque dimensions.

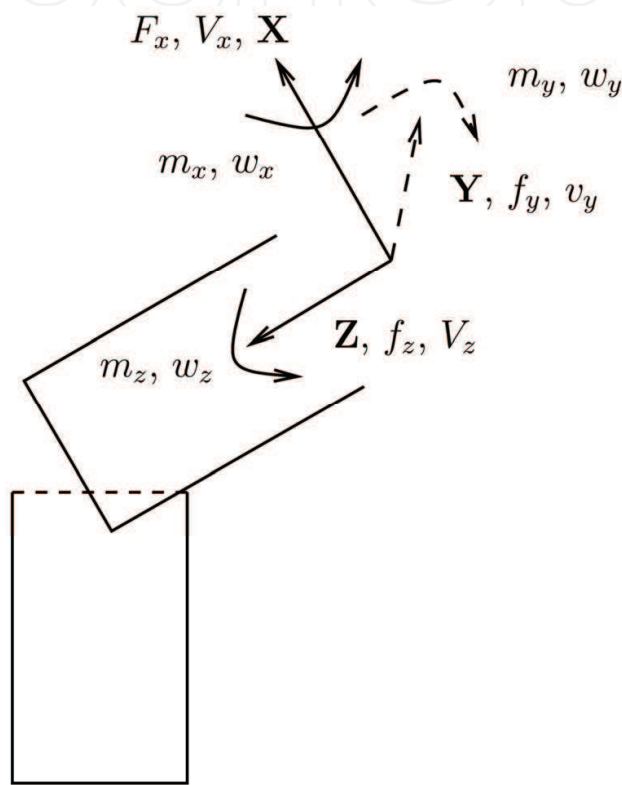


Figure 4. Peg-on-hole with a three point contact. Cartesian axes in peg coordinates. Representation of the forces and velocities (6 DOF). w_y represents the alignment velocity and v_z the insertion velocity

Control Matrices

The state feedback gain L_r is computed for a critically damped response with closed loop time constant τ_c equal to

$$\tau_c = 10T_p.$$

(68)

The other poles due to dead-time are mapped in the z -domain at $z = 0$ (discrete poles). The reachability matrix W_c and the characteristic polynomial are described in the AOB algorithm (see Sections 5 and 6).

7.4 Experimental Results

The execution of the peg-in-hole task starts with the peg-on-hole with a three point contact. The Cartesian axes and the corresponding forces and velocities are represented in Figure 6.4 in peg coordinates. If the peg is perfectly aligned, the angular velocity w_y (negative sign) aligns the peg in vertical position, while f_x (negative sign) and f_z (positive sign) guarantee always a three point contact during the alignment phase. Then, only the velocity v_z is needed to put the peg into the hole. Non-zero m_y and f_x reinforce contact with the hole inner surface during insertion. Ideally, the relevant signals for the alignment phase are f_x , f_z and w_y , and for the insertion phase are v_z , m_y and f_x . Figures 6.5 and 6.6 show force/velocity data¹⁰ for the peg-in-hole task, applying different control strategies. An artificial neural network (ANN) trained with human data generates the desired compliant motion signals (velocity and force) from pose sense. Figures 5 and 6 present results when the AOB-1, HBA is applied to all directions except the z direction that has the CKF, SBA. The moment m_y is only function of the contact forces and of the contact geometry during the alignment phase [Koepe, 2001]. Hence, the controller for m_y is only active during the insertion. f_x , f_y , m_y , m_z , and the corresponding velocities v_x , v_y , w_y and w_z follow well the reference signals (Figures 5.a, 5.b, 5.e, 5.f and Figures 6.a, 6.b, 6.e, 6.f, respectively). There is a slight misalignment in the peg during the alignment phase which originates a moment m_x (Figure 5.d). The CMC reacts issuing an angular velocity w_x represented in Figure 6.d. The insertion velocity v_z is slightly biased during the alignment phase (Figure 6.c). These errors come from imperfect training of the ANN ([Cortês et al., 2004]). Therefore, the force f_z is seriously affected by v_z errors. The stiffness in z direction is high (Table 1), magnifying even more feedforward errors. An overshoot of almost 20 [N] is reached before insertion creating a barrier to the task execution speed due to force sensor limits (Figure 5.c). An error of 4 [N] in f_z (at the beginning of the alignment phase) is due to feedforward velocity errors (see Figures 5.c and 6.c.). Since no active control actions are done for the z dimension, the degradation of the control performance is evident, stressing the importance of AOB actions.

8. Conclusions

The first part of the chapter discusses model-reference adaptive control in the framework of Kalman active observers (AOBs). The second part addresses experiments with an industrial robot. Compliant motion control with AOBs is analyzed to perform the peg-in-hole task.

The AOB design is based on: 1) A desired closed loop system, corresponding to the reference model. 2) An extra equation (active state) to estimate an equivalent disturbance referred to the system input, providing a feedforward compensation action. The active state is modeled as an auto-regressive process of order N with fixed parameters (evolutions) driven by a Gaussian random source. 3) The stochastic design of the Kalman matrices (Q_k and R_k) for the AOB context. Q_k has a well defined structure. Most of the modeling errors are merged in the active state, therefore, the model for the other states is very accurate (the reference model has low uncertainty). The relation between Q_k and R_k defines the estimation strategy, making the state estimates more or less sensitive to measures.

¹⁰ The measured force/velocity signals were filtered off-line by a 6th order low-pass Butterworth filter with a 2 [Hz] cut-off frequency. The phase distortion was compensated.

Experiments with the peg-in-hole with tight clearance have shown the AOB importance in the control strategy. When there are relevant inconsistencies between force and velocity signals, non-active control techniques give poor results. For complex compliant motion tasks, on-line switching between AOB and classical Kalman filter (CKF) is easy, since the CKF is a particular form of the AOB which does not require extra computational power.

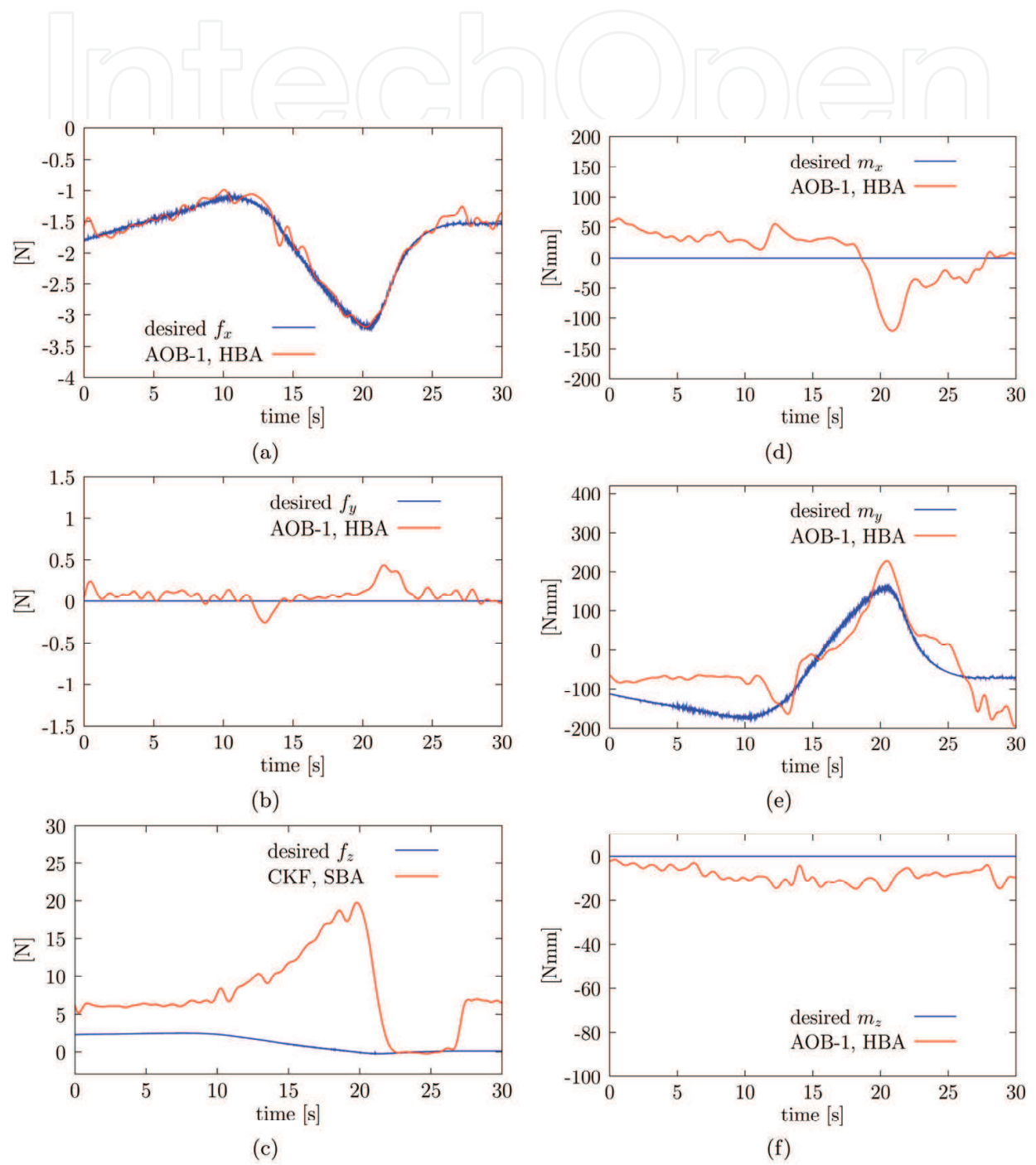


Figure 5. Experimental results for the peg-in-hole task with scale 10 (i.e. ten times slower than human demonstration). AOB-1, HBA vs. CKF, SBA. Force data. f_z always with CKF, SBA

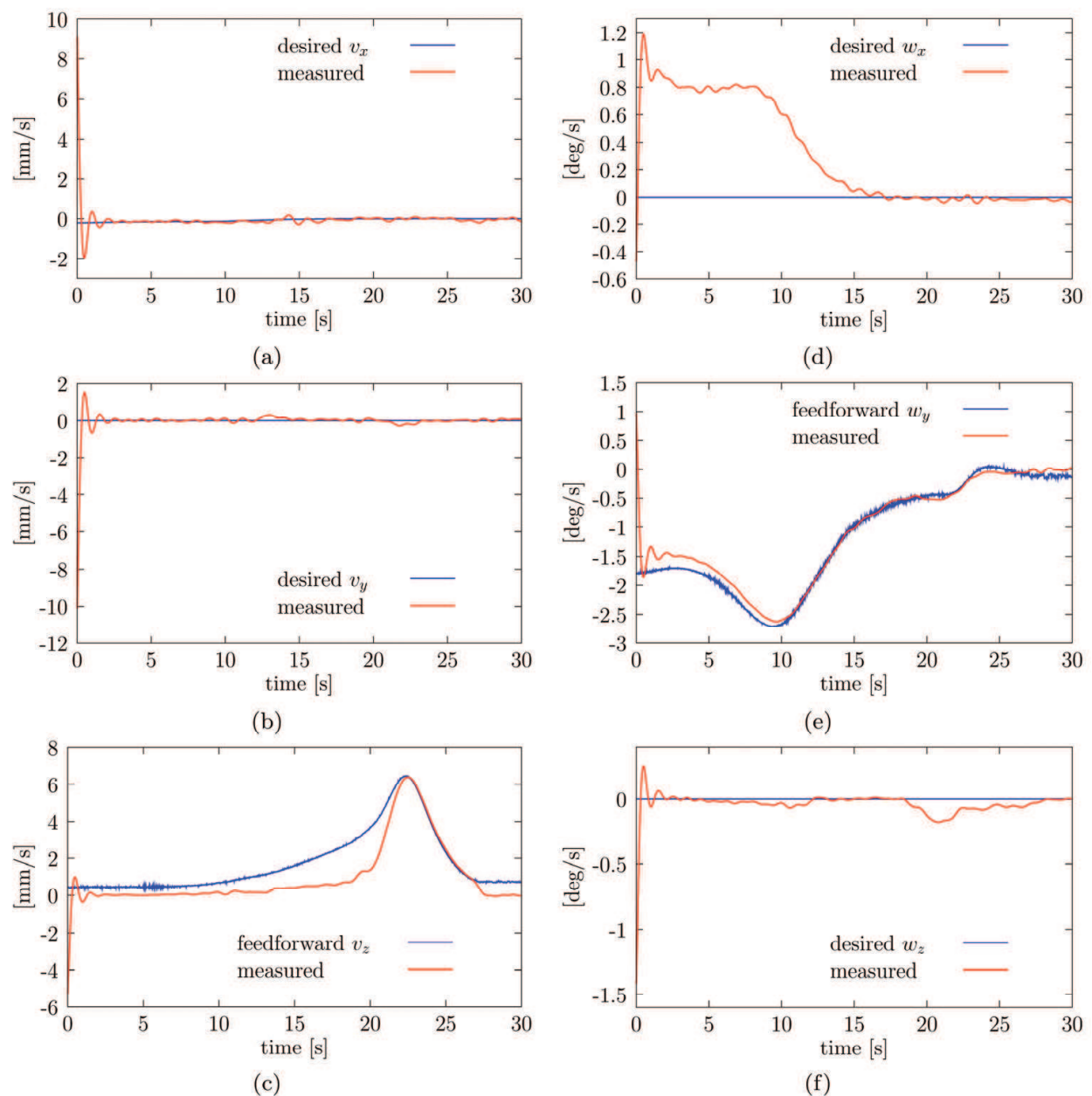


Figure 6. Experimental results for the peg-in-hole task with scale 10. AOB-1, HBA vs. CKF, SBA. Velocity data. f_z always with CKF, SBA

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