

Peg-in-Hole assembly using Impedance Control with a 6 DOF Robot

Jan F. Broenink[†] and Martín L.J. Tierneho[‡]

[†]Control Laboratory, EE Department University of Twente, P.O. Box 217, NL-7500 AE Enschede, Netherlands
phone +31 53 4892793; fax +31 53 489 2223; e-mail J.F.Broenink@el.utwente.nl

[‡]Royal Military Academy, P.O. Box 90154, NL-4800 RG Breda Netherlands

ABSTRACT

To gain insight in problems of industrial assembly operations, an anthropomorphic robot equipped with a vision system was used to insert differently shaped pegs into corresponding holes of a plastic ball. Spatial impedance control was used, to properly deal with the interaction between robot and environment and to elegantly chose the impedance of the robot.

Simulations gave insight into the behavior of the manipulator during free motion and during contact. Experimental results complied with simulations, but contact forces appeared to be higher than the simulated ones.

Keywords: CIME, Control Systems, Bond Graphs, Parallel computers.

1. INTRODUCTION

In industrial manufacturing applications, parts mating or assembly operations occur frequently. Robots must successfully plan and execute tasks in the presence of uncertainty, for example positioning uncertainty. Since many tasks involve object interactions, these tasks are subject to uncertainty arising from errors in object-position sensing and control. To gain insight in the problems of assembly operations we used our anthropomorphic robot equipped with a vision system to insert differently shaped plastic pegs into corresponding holes of a plastic ball (Korsten and Wijbrans, 1990), which actually is a child's spatial puzzle (a Shape-O-Toy), called the "Hollebol". The work reported here is extensively described in the MSc report of Bonnes and Colard (1994).

This contribution describes the topic of the assembly task and especially how a *bond-graph* based point of view supports the process of controller design, simulation and implementation on a parallel computer system, in our case a transputer system. (With *bond-graph* based, we mean an angle of thinking from physical systems theory, i.e. we model systems as interacting parts which exchange energy.) Assuming that the information of the types of the pegs and holes, and their position and orientation is available through the vision system, the robot system should perform the assembly task. Determination of appropriate grasping and insertion strategies was a significant topic, since neither the accuracy of the robot nor the accuracy of the visual position detection determination was sufficient enough to insert the pegs in the holes in a straightforward way.

In this paper, first we will describe why we have chosen for impedance control. Next we will give a brief description of the control algorithm, without going into detail. A first step in the realization was to perform simulations. Some of the results will be given. We will conclude with the implementation in the hardware and some experimental results. Besides this we will give some comments on the usefulness of simulations in combination with experiments.

2. IMPEDANCE CONTROL

It is clear that during insertion, the robot must somehow accommodate its motion due to contact forces between the end-effector and the environment. Accommodation can be achieved by either passive means (Whitney, 1982) or by active control Raibert and Craig, 1981). Active accommodation has the advantage of being adaptable to various applications and it does not need beveled pegs or chamfered holes. However, active accommodation has the disadvantage that the complexity of the controller increases. In our case, since the holes are not chamfered and the pegs are not beveled, we cannot use passive accommodation.

Different strategies for force feedback exist (Whitney, 1987): *Force Feedback*, where forces are used rather than positions or velocities, *Hybrid Control*, where in some directions force control is used and in the other orthogonal directions 'normal' position control, *Stiffness Control*, where the apparent stiffness of the manipulator is controlled: the controller behaves like a variable spring, *Damping Control*, where the damping of the manipulator is controlled and *Impedance Control*, which is actually a generalization of stiffness control and damping control. Here, the dynamic interaction between the manipulator and its environment is controlled. Furthermore, impedance control enables contact between manipulator and environment, without making the system unstable during the passage from free motion to contact (Hogan, 1985). The controlled manipulator interacting with the environment can be seen as mass-spring-damper system, behaving like an impedance towards the environment. Explicitly modeling the damped compliance behavior of the interaction between manipulator and environment yields the model of Fig 1. In case of moving in free space the contact impedance vanishes.

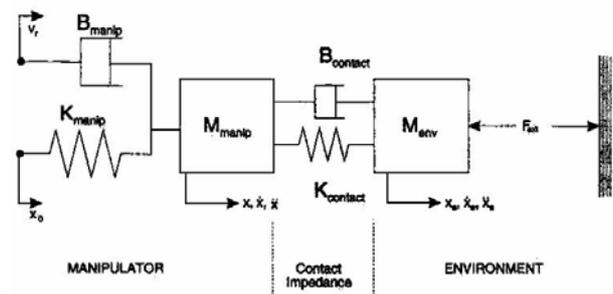


Figure 1a: Model of dynamic interaction, mechanical diagram

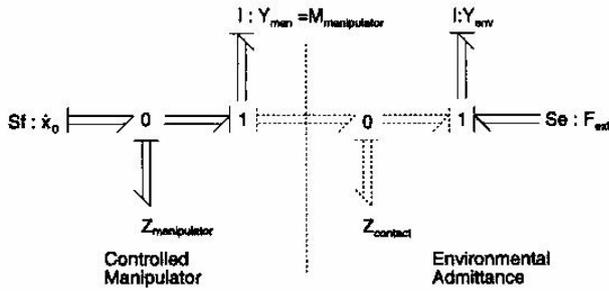


Figure 1b: Model of dynamic interaction, bond graph

Hence, as the low level controller, we used *impedance control* since a considerable interaction with the environment takes place during insertion and contact instability does not occur using impedance control. At this point the bond-graph based angle of reasoning is used, since it structured our way of dealing with the control of the interaction

However, a problem associated with impedance control is that it is difficult to select the impedance given the task descriptions. Selection is difficult when axis relevant to the task are not aligned with the so-called robot endpoint frame. A solution is to use a second frame aligned with relevant task axis, a so called task frame. One can plan impedance using the task frame and transform the impedance to the endpoint frame. However, this is, computationally intensive, and unnecessarily complex and inelegant.

In the control of robots, configuration of objects is commonly represented using a set of six independent coordinates. Orientation, in particular, is commonly represented using angles of rotation, such as Bryant angles. In our case, orientation is represented using rotation matrices, as is common in robotic kinematics but uncommon or unique in control. The rotation matrix can be identified with a set of orthonormal vectors, or a frame, attached to the body of interest. In general, three such frames are used, one attached to the robot i.e. end effector, a second one to the environmental body of interest (in our case the hole of the Hollebol, and the third one to an instantaneous (virtual) equilibrium position, i.e. the setpoint of the position loop of the controller (Fig. 2). The effect of the controller is the alignment of the robot end-effector frame to the virtual equilibrium frame. This configuration can also be considered as a varying compliance be connected between the robot frame and the virtual equilibrium frame. This approach is referred to as *spatial impedance control* (Fasse and Broenink, 1996; Fasse, 1995). The representation of the *position*, is the usual Cartesian coordinate representation. For instance, the position of the end-point, x_r , and the equilibrium position, x_e , are

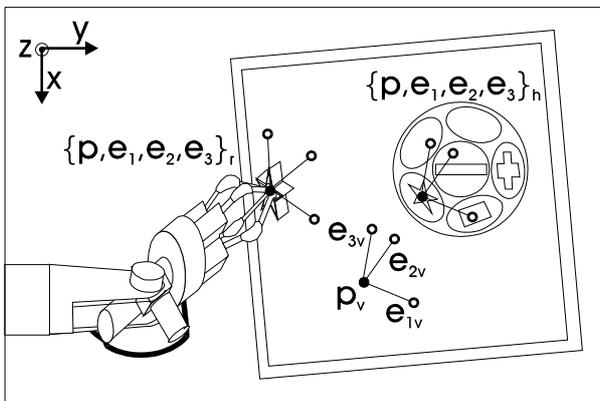


Figure 2: The three frames used for impedance control.

given in terms of the world coordinates.

3. MOTION PLANNING

Assembly of the Hollebol can be seen as a complex 'peg-in-hole' problem. These kind of tasks need careful planning. Especially the fine-motion tasks like grasping the peg and inserting the peg into the correspondingly shaped hole need attention. How these fine-motion tasks can be performed depends on both the robot, i.e. its gripper and its movement possibilities, and the pegs, i.e. their shape and their position and orientation while being grasped.

The pegs we used are 10 differently shaped pegs which all are partly hollow. Examples of shapes are: circular, triangular, pentagonal, plus shaped, star shaped. The hollow space inside the pegs is used to grasp the peg, such that it is possible to manipulate them into the corresponding hole directly, i.e. the gripper does not hinder insertion, necessitating regrasping. The gripper has four fingers which are coupled in two pairs of opposite fingers. The fingers are round pins of 3 mm diameter. This implies that a clearance of 5 mm is left for grasping the peg with the smallest inside space (i.e. the triangle). Round fingers give a stable grasp, since while picking up the peg (i.e. opening the gripper) the fingers move to the corners of the peg. By using a predefined orientation, the end configuration of the peg-gripper combination is as desired.

Inserting the peg into the hole cannot be done straightforward, since the tolerance of the robot is larger than the clearance of the peg and hole. We used peg tilting, a strategy similar to one commonly used by humans, in which blocks are first tilted to ease initial insertion, aligned with respect to the holes and then pushed through. For each peg, a initial orientation and tilting angle is derived in order to guarantee a sophisticated insertion.

The reason for choosing peg tilting is that it can be used for differently shaped pegs and has proven successful in peg-in-hole insertions having a clearance of tenths of millimeters (Strip, 1988). Furthermore, relatively low computational power is needed.

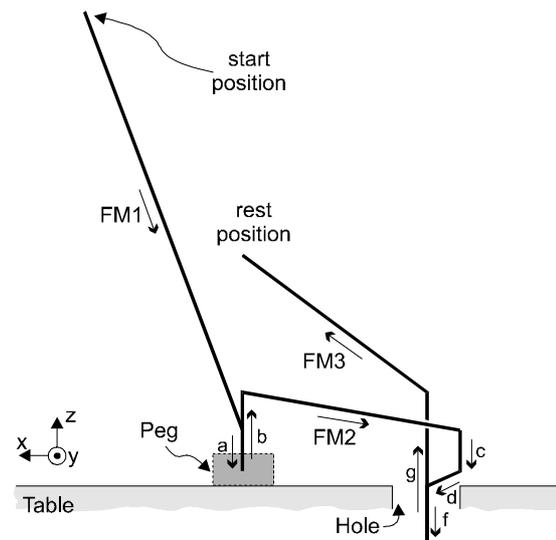


Figure 3: A typical end point trajectory, front view

The insertion part of the assembly task has the following sequence (see Fig 3 for an example):

- The robot is in a position above the hole, grasping the peg in a known orientation

- Move down onto the edge of the hole, using the predefined orientation and tilting angle
- Slide the peg into the corner of the hole
- Tilt back the peg
- Push the peg into the hole, and release the peg
- Move up (to the rest position)

4. CONTROLLER DESIGN

The robot model of the OSCAR-6 robot is given by the standard equation of motion:

$$\mathbf{M}(\theta)\ddot{\theta} + \mathbf{C}(\theta, \dot{\theta})\dot{\theta} + \tau_{gr}(\theta) + \tau_{fr}(\theta, \dot{\theta}) = \tau_{act} + \tau_{int} \quad (1)$$

where τ_{gr} and τ_{fr} represent effects of gravity and joint friction, τ_{act} and τ_{int} the interaction and actuator torques.

An important part of our robot control system is the low-level impedance controller. The overall structure of the impedance controller is quite standard:

$$\tau_{act} = \tau_{-gr}(\theta) + \tau_{-fr}(\theta, \dot{\theta}) + \tau_{comp}(\theta) + \tau_{diss}(\theta, \dot{\theta}) + \tau_{ff}(\theta, \tau_{int}) \quad (2)$$

Effects of gravity and joint friction are partially compensated (τ_{-gr} and τ_{-fr}), to give the robot (ideally) the behavior of a serial linkage of rigid bodies. Compliance and damping terms are used to give the robot a desired endpoint behavior (τ_{comp} and τ_{diss}). Additionally, force feedback is used to reduce the apparent inertia and uncompensated friction of the robot.

The compliance term, τ_{comp} , gives a static relation between input displacement of the end-point with respect to the desired equilibrium position (and orientation), and the actuator torques. This term is based on a potential energy, U , of the 'virtual' spring which can be thought to be connected between the robot end point (tool center point) and the target position (the center of the hole on the surface of the hollebol).

$$U = \frac{1}{2}(\mathbf{p}_r - \mathbf{p}_v)^t \mathbf{K}(\mathbf{p}_r - \mathbf{p}_v) - \kappa_1 \mathbf{e}_{1r}^t \mathbf{e}_{1v} - \kappa_2 \mathbf{e}_{2r}^t \mathbf{e}_{2v} - \kappa_3 \mathbf{e}_{3r}^t \mathbf{e}_{3v}$$

The first term is the energy function of a translational spring with stiffness \mathbf{K} . It acts to conicide points \mathbf{p}_r and \mathbf{p}_v . The other terms represent the energy of the rotational compliances. Then the partial derivative of U with respect to the joint coordinates θ yields the compliance term of the controllaw.

The damping term, τ_{diss} , gives a relation between the end-point velocity (with respect to a reference velocity) and the actuator torques. We used joint damping in stead of end-point damping (like with compliance) because it is easier to implement and easier to tune.

The force feedback term, τ_{ff} , gives the relation between the forces applied on the end-point and the actuator torques, and is a straightforward transformation from measured forces to actuator torques using the Jacobian. Furthermore a scale factor γ is introduced to investigate the contribution of τ_{ff} . Since the friction is not negligible (one of the wrist joints has considerable stick), we designed a friction compensator based on both the angle and the velocity of the joint.

5. SIMULATION

Modeling and simulation was done in 20-SIM (formerly named CAMAS), a bond graph and block diagram modeling and simulation program running on SUN, Windows95 and Windows3.11 (Broenink, 1990; Controllab Products, 1995). The top-level simulation model of the controlled robot is shown in Fig. 4.

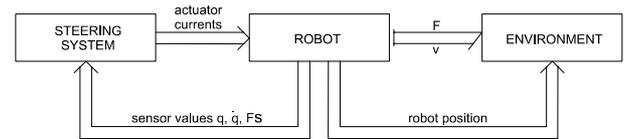


Figure 4: Top level of the simulation model

The manipulator interacts with the *environment*, which is modeled by a spring-damper system. In the robot submodel, the computations for the Jacobean are modeled separately from the equations of motion of the robot. The steering system consists of a supervisor and an impedance controller. The supervisor determines the end-point equilibrium position and orientation, as well as the desired values of manipulator stiffness and damping during the different phases of the assembly task. For each different kind of task, a task controller was modeled. In the impedance control submodel, the actual control law is separated from the kinematic computations. This way of structuring the model enabled us to easily exchange the control law, which was done using hybrid control (van der Vegt 1995).

The simulation (Fig. 6) shows the sensor forces using force feedback. Now lower values of the stiffness and damping parameters can be used then without force feedback. In this case not only the impact forces decrease, but also the contact forces after the impact force are about one-third of the ones at no force feedback and using higher stiffness and damping. During grasping the peg the impact force is 7.1N; the contact force is 3.0N. During the peg-in-hole phase, impact forces of 5.3N and 6.7N for F_n occur when the peg arrives on the corner of the hole and when the peg is actually inserted into the hole, respectively.

Other simulations showed that the impact forces, as well as the contact forces after impact can be influenced by changing stiffness parameters. Changing damping parameters only influences the impact force and the fluctuation of the force after impact.

Other aspects which may influence interaction forces between manipulator and environment are the scale factor γ of τ_{ff} . Since interaction forces should be kept in control during the assembly task, it is useful to observe the relation between interaction forces and either γ or the equilibrium point \mathbf{x}_v . Fig. 5a shows the relation between γ and the impact and contact forces. The figure shows that the impact force becomes infinite for $\gamma=-1$ which corresponds to the fact that the desired inertia of the manipulator is high. The impact forces as well as the contact force after impact depend linearly on the equilibrium position (Fig. 5b).

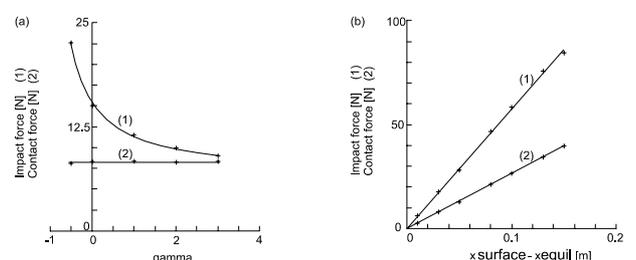


Figure 5: Impact and contact forces versus: (a) γ (b) x_v

An important goal of simulation was to verify the correctness of the newly developed impedance controller. Although not elaborated here, some errors in the *controller* software were elimi-

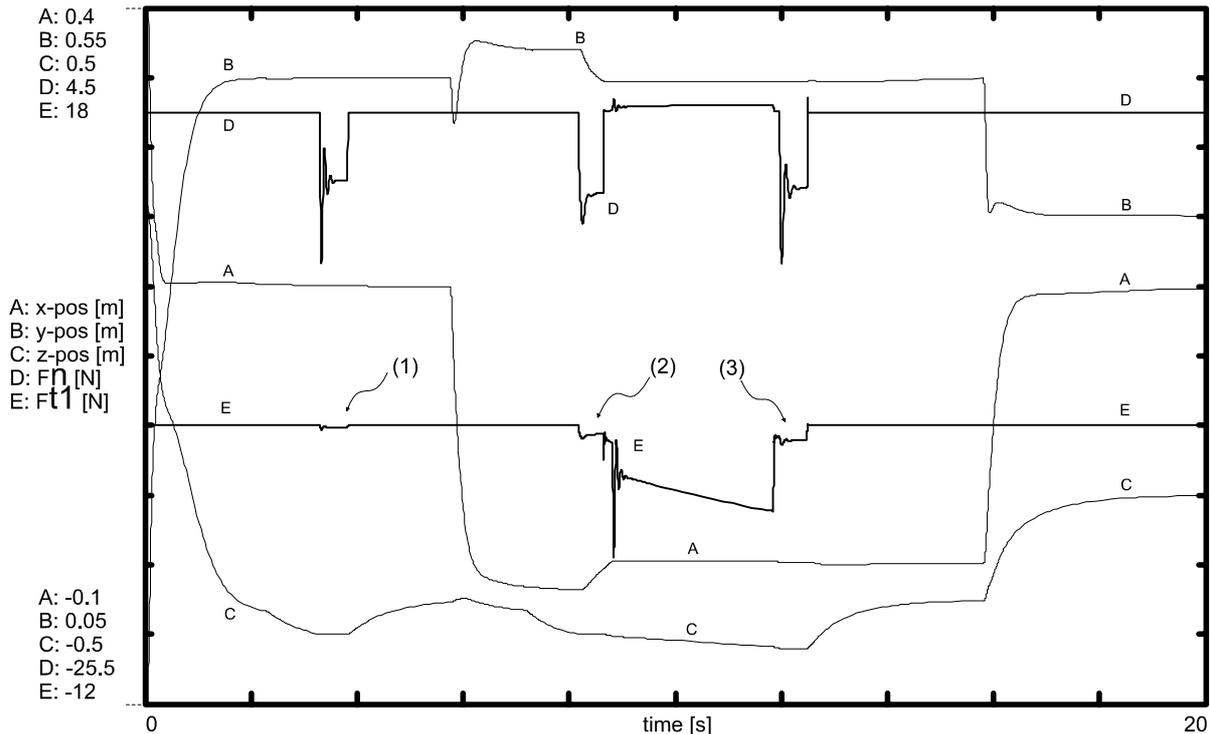


Figure 6: Simulation of Forces F_{e1} and F_{e2} (denoted in the plot as F_n and F_{t1})

nated, in order to achieve correct operation of the controlled system.

By performing simulations, insight is gained into the behavior of the controlled system under various conditions. The simulations show that a low apparent (effective) inertia of the manipulator is preferable. A lower apparent inertia is achieved by using force feedback, which not only decreases forces during impact with the environment, but also makes it possible to achieve lower apparent stiffness and damping parameters. By using these lower impedances the contact forces can be kept below 5N. The simulations also show how parameter changes influence the behavior of the manipulator in unconstrained motions as well.

Although the simulation model is a simplification of the reality, it appears that the simulations are useful towards implementation. The simulation model predicts:

- Correct operation of the impedance controller.
- Behavior of the manipulator during free motion.
- Impact forces and steady-state forces during interaction with the environment.
- Duration of the assembly task.

6. IMPLEMENTATION

The impedance control system is implemented in OCCAM-2 using the transputer network system. A full description of the transputer network and the network layer implemented in OCCAM-2, is presented in Tigchelaar (1994).

The control law process is placed on one transputer. This process calculates the steering values and sends it to the safety system of the robot. The safety system samples at 250 Hz (sampling period of 4 ms). If the calculation of the steering values takes more than 2.4 ms, the safety system will shut down the whole system and generate a "Link time-out error" message. This safety system is built in due to the use in an experimental environment. Although it is conceptually undesirable, for practical reasons, the calcula-

tion of the force feedback term, is located in the kinematics process which is partitioned over four transputers.

First, experiments were done using a *flat plate* which has holes shaped and chamfered identical to the hollebol. Then pegs were inserted in the accessible holes of the hollebol which was attached to a sturdy base.

At tests with the peg-in-hole controller, it appeared that during sliding to the corner and tilting back, the peg was losing contact with the hole, so the shifting direction was chosen more 'inside' the hole (n-direction), in order to keep contact with the hole. Also it appeared that due to high contact forces, the flat plate slid. The contact forces were on the order of 20 N. The contact forces were controlled by means of shifting the equilibrium position based on force information. This resulted in contact forces of in the order of 5 to 10 N, measured by monitoring the force (Tigchelaar, 1994). Fig. 7 shows histories of the vertical component of \mathbf{p}_T and the normal component of \mathbf{f}_T during a successful assembly try on the flat plate. t_1 denotes the initial contact of the end-effector with the block. t_2 denotes the initial contact of the block with the hole. Tangential contact of the block with the hole occurs at time t_3 , while the block is released at t_4 .

In implementation, the contact forces appeared to be higher (about two times) than in simulation. This can be explained by the fact that the simulation model is a simplification of reality. Especially stiction showed to be a problem that was not modeled in simulation. These stiction forces had to be better compensation for in order to obtain lower contact forces.

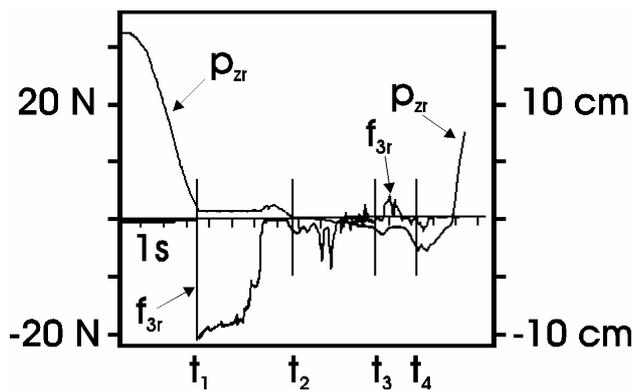


Figure 7: Practical results

However, the simulations were a helping hand in obtaining useful parameter values. The simulations gave insight into the behaviour of the manipulator during free motions and during impact.

7. CONCLUSIONS

A general control strategy, *impedance control*, was investigated for controlling a manipulator which may interact dynamically with its environment. The conventional representation of object configuration, using roll, pitch, and yaw angles, was seen to be ill suited to the task. In particular, impedance selection was difficult given the task description. Therefore, using rotation matrices and Cartesian coordinates gave an alternative representation of configuration, which facilitated the selection of impedance with respect to the task. A force feedback term, also based on this alternative representation, was added in order to decrease contact forces. Although the controller appeared to be computationally intensive, it was found that if the conventional representation was used, the amount of calculations would be more intensive and complex.

However, implementation of the grasping and insertion strategy, and the novel impedance controller showed that, due to inadequacy of the model, the simulations did not predict problems, associated with friction. A new friction compensator improved the positioning repeatability, and diminished the stick-slip effect and oscillations of the OSCAR-6 robot. All pegs can be inserted into the corresponding chamfered or chamferless holes of the flat plate, having a surrounding clearance of 0.5 mm between peg and hole. Contact forces occurring at interaction with the environment lower than 10 N were achieved.

Using a bond-graph based point of view indeed supports the process of modeling the robot with its controller. This is especially in our case fruitful, since interaction between robot and environment occurs.

For further research we plan to use the current impedance controller for other tasks, such as grinding.

REFERENCES

- Bonnes, A.J. and G.B.J. Colard (1994), *Peg-in-hole assembly with the Oscar-6 robot using impedance control*. MSc. Thesis reportnr. 021R94, Control Laboratory, Dept. EE, University of Twente, Enschede, The Netherlands.
- Broenink, J.F., (1990) Computer aided Physical systems modeling and simulation: a bond-graph approach, PhD. Thesis University of Twente, Enschede, Netherlands.
- Controllab Products, (1996), *20SIM Reference manual*, Control-lab Products, Enschede, Netherlands.
- Fasse, E.D., (1995) Simplification of Compliance selection using spatial compliance control, Proc. ASME IMECE meeting 1995.
- Fasse, E.D. and J.F. Broenink, (1996), A Spatial impedance controller for robotic manipulation, accepted for publication in *IEEE Trans Robotics and Automation*.
- Hogan N. (1985), Impedance Control: An Approach to Manipulation: Part I - Theory; Part II - Implementation; Part III - Applications. *ASME Journal of Dynamic Systems, Measurement, and Control*, **107**(1), pp. 1-24.
- Korsten, M.J., Wijbrans, K.C.J. (1990), *Flat Plate Project*. Internal report, reportnr. 90R017, Control Laboratory, Dept. EE, University of Twente, Enschede, The Netherlands.
- Raibert, M.H. and J.J. Craig, (1981), Hybrid position/force control of manipulators, *ASME J. of Dynamic Systems Measurement and Control*, **102** pp 126-133.
- Strip, D.R. (1988) Insertions using geometric analysis and hybrid force- position control: methods and analysis *Int Conf on Robotics and Automation*, **3** pp 1744-1751.
- Tigchelaar, T.J. (1994), *Enhancement of the OSCAR-6 Robot with Vision*. MSc. Thesis reportnr. 020R94, Control Laboratory, Dept. EE, University of Twente, Enschede, The Netherlands.
- Van der Vegt, H.W.A., (1995), Hybrid control for the OSCAR-6 robot, MSc. Thesis reportnr. 95R018, Control Laboratory, Dept. EE, University of Twente, Enschede, The Netherlands.
- Whitney, D (1982), Quasi static assembly of compliantly supported rigid parts, *ASME J. of Dynamic Systems Measurement and Control*, **104**: 65-77.
- Whitney, D., (1987) Historical perspective and state of the art in robot force control, *J. Robotics Research*, **6**(1), pp 3-14.