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Models And Control for Force/Torque Sensors in Robotics

Gert Johansson

Assembly Technology

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Institute of Technology, Dept of Mech Eng, S-581 83 Linköping, Sweden

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One of the important problems in automatic assembly is the relative positioning accuracy between the parts in the assembly process. Inaccurate positions can hinder succesful assembly.

This thesis presents a solution based on active feedback of force/torque data from a wrist mounted sensor. A task independent control algorithm transforms force/torque input to relevant motion of the end effector. The transformation, called the sensor model, is specified by e.g. desired forces, compliance and stopping criteria. An algorithm and a calibration sequence for the compensation of end effector gravity forces are developed. To allow necessary modifications and expansions for the integration of sensors, an open and general control system architecture is proposed. The architecture is based on a computer workstation and pipelined Transputers.

The thesis is divided into two parts, the first is a summary and introduction of the authors work. The second part is an appendix including three internationally published papers:

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Abstract

One of the important problems in automatic assembly is the relative positioning accuracy between the parts in the assembly process. Inaccurate positions cause large insertion forces, wear and might damage the parts. They can also completely disable the assembly process. A solution to this problem is to detect the positioning error and to make a relevant adjustment of the position or path.

This thesis presents a solution based on active feedback of force/torque data from a wrist mounted sensor. A task independent control algorithm has been realized through a sensor model concept. The sensor model includes an algorithm that transforms force/torque input to relevant motion of the end effector. The transformation is specified by a set of parameters e.g. desired forces, compliance and stopping criteria. The problem with gravity forces for varying end effector orientation is compensated by an algorithm, divided into three complexity levels. The compensation method includes a calibration sequence to ensure valid end effector properties to be used in the algorithm. A problem with available robot technology is bad integration possibilities for external sensors. To allow necessary modifications and expansions, an open and general control system architecture is proposed. The architecture is based on a computer workstation and Transputers in pipeline for the robot specific operations.

The thesis is divided into two parts, the first is a summary and introduction of the authors work. The second part is an appendix including three internationally published papers:

1. General Parametric Sensor Model with External Communication Possibilities

2. Towards Common Infrastructure for Advanced Manufacturing Control Systems

3. An Efficient Mass Compensation Method for Force/Torque Control in Robotics

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1. Introduction

1.1 The flexibility problem

Today companies have to compete hard to survive and get market shares. Several factors have to be improved to achieve good profit and the ability to develop new competitive products. Some important factors are product quality and design, adaptation of the products to simplify manufacturing (DFM), lean production with a minimum of buffers, short setup times for different variants of the product and the factory organization. These factors can of course have various impact in different cases. A factor where improvements always are possible and can give a direct result is the production. The production has to be efficient and flexible to meet the customers requirements of variants and new models. As lifetime cycles for industrial products gets shorter, Flexible Manufacturing Systems (FMS) become more advantageous. The basic idea of flexible production is that the equipment and staff shall produce products instead of using the time for reconfiguring the factory or the individual machines. If the equipment and factory organization are prepared for the change of variants and new models or products, a minimum of exchange time will be needed. Manufacturing systems can be flexible in a technical sense, but also in economical terms. A technically flexible equipment is usually recognized by short exchange time for different products and can easily be modified for new products. In economical terms, a rigid system can also be flexible. If the system is very cheap and can be easily replaced or rebuilt at a low cost when it is time to change for a new model it can be a better choice than flexible equipment which usually is more expensive. Long series and few variants are traditional requirements for rigid systems to be cost effective.

This thesis will only deal with the technical aspects of flexible equipment. That is technical solutions that increases the possibilities to make adaptations to new products or new conditions. The industrial robot is a good example of a technically flexible equipment which can be used in many different applications. However, robot adaptations to new products requires new programs and perhaps new end effectors and environmental equipment. Programming a robot is often time consuming and on-line teaching of robots when stopping production is seldom acceptable. Off-line programming is more advantageous since the complete program structure can be built outside the robot without stopping the production. Still, most positions in the robot program must be taught in the real robot environment, which causes interrupts in production. The first period in the history of a new production line usually requires major adaptations and adjustments to eliminate error sources. The adjustment period might often be long and costly. At the same time the production rate will be lower than the nominal. If the product mix is very rich of variants, these adjustment periods might be quite considerable.

1.2 Solving a part of the flexibility problem

To some extent, active sensor support can solve the problem of expensive and less productive adjustment periods. Examining robotic assembly installations shows that a great deal of the problems are focused to the contact motions. The problem increases with narrow tolerances and causes excessive forces when the relative mating positions are inaccurate. If the tolerances are tighter than the repositioning accuracy of the robot, there will always be mating forces of varying magnitude and direction. The assembly forces might damage the parts and cause high wear on fixtures and end effectors. Another error source is the fixturing of the base part. Tolerances and wear of the fixtures causes more positioning inaccuracy outside the robot structure. Wear of fixtures and end effectors, thermal effects etcrequires adjustments of robot positions to be done more or less regularly, it might also cause stop in production. Another problem source is defective parts that can disturb the assembly process. These problems might decrease the possibility of unmanned production, which otherwise could be profitably. A sample solution can be to use vision for identifying and locating objects to be gripped, instead of arranging specific feeders and fixtures. Force/torque sensing can control the mating of parts to avoid large forces and wear [Johansson, 1988]. It can also detect large forces resulting from defective parts. The drawback is that when a traditional production line is adjusted and working properly, it is faster than using sensors for all critical operations. This statement is of course only valid if it is possible to perform sensor-less production. A conclusion is that systems with sensors can not compete with sensor-less systems in long series production, only for short series where fixturing costs etc will be too high. The concept outlined here is to use sensors (read force/torque sensors) mainly for programming, supervision and adjustments. The benefit is that the comparatively slow active sensor control is used only when it is necessary. Sensors are then used to adapt theoretical positions to the real ones, the first time a new robot program is executed. Thereafter sensors are used mainly for supervision and to correct operations that are unsuccessful. The performance of this kind of system is equal to conventional sensor-less ones, since sensors are just supervising and does not slow down the execution of the robot program. The sensor based system has the advantage of being better during the adjustment period and for detecting and correcting errors.

As outlined, sensors can give a good contribution to flexibility in FMS. Generally, a complex and advanced sensor can give more nuanced information about the actual state, on the other hand it is often demanding to extract this information. Therefore it is important to categorize the information and transform it into a format, easy to handle. The ultimate goal must of course be to achieve real time performance for advanced sensor control, allowing them to be active in every critical operation. This goal must be seen in a longer perspective, but with a relevant control system architecture with high computational power and higher sampling rates, this might be possible.

This thesis is based on three papers dealing with different aspects of sensor control of industrial robots. The research work has concerned a "sensor model concept" for a force/torque sensor, requirements and architectures for robot controllers and an algorithm to make force/torque sensors more independent of orientation changes with respect to end effector mass.

2. Problem description

The presented work has been carried out in the area of automated assembly. Great emphasis is put on the flexible assembly systems (FAS), where the industrial robot is studied as it is a flexible and important piece of equipment. Other related projects at the department are concerning: economy in assembly systems, the design of assembly systems, design for assembly, product modelling, robotic assembly program generation, robot vision, programmable compliance, and this project concerning sensor models and robot control. The focus has been set to the assembly process where the contact based motion has been of major interest. The real problems in assembly becomes obvious when contact is reached. Assuming that no defective parts exist, there is theoretically no problem with assembly processes as long as positioning and path accuracy are absolute. In practice though, there will always be minor position and orientation errors, see figure 1. These errors will cause forces and torques when parts are being assembled. If the assembly forces are large, the parts can be damaged or the the insertion might be impossible. Just refining the robot accuracy is not enough to solve the assembly problem. The rest of the assembly station does also include inaccuracies: fixture and feeder positions, inaccurate grippers etc. Even temperature changes can cause varying positions. The resulting forces are functions of the tolerances of the assembled parts and the position error, see figure 2.

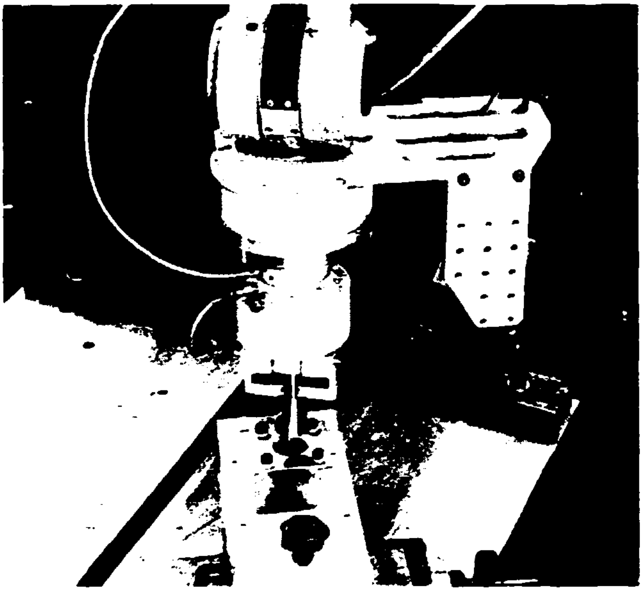

Figure 1. Experimental setup for the force/torque guided insertion of a peg into a chamfered hole

Another factor which is very important for the assembly process is the design of all parts. Compare the hole and shaft in figure 3. The chamfer of the hole

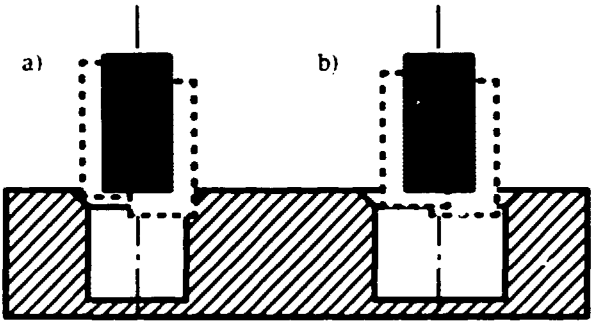

Figure 2. a) tight tolerance and bad accuracy causes contact forces.
b) Loose tolerances allows insertion without contact forces.

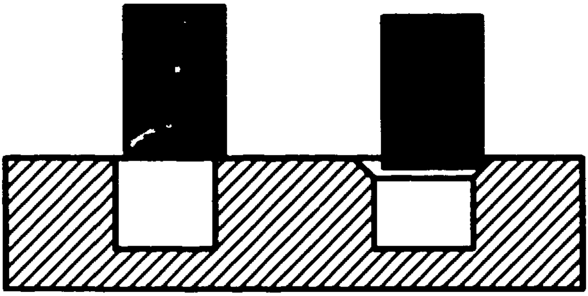

Figure 3. Design for assembly has great impact. The chamfer can guide the peg into the hole.

and or the shaft is a good example of design where the assembly process has been considered. Assuming some compliance in the system, it is obvious that the chamfer can guide the shaft into the hole even with some lateral errors. Without the chamfer this is impossible, the position has to be perfect for a direct fit.

If lateral errors causes forces that can damage the parts and even make insertion impossible, orientation errors might cause jamming and wedging. Jamming is a phenomenon, similar to closing a drawer with to much force applied on either left or right side. The drawer gets stuck as it is tilted slightly and gets into a diagonal two point contact, see figure 4. Wedging is principally the same as jamming but more ill conditioned. It occurs with specific ratios between diameter, length, tolerance, friction and elasticity. Wedging is charac-

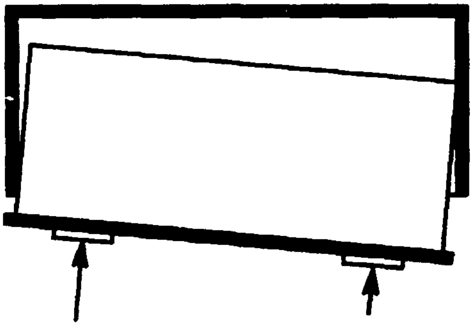

Figure 4. The drawer gets stuck (jamming) because of unequal applied forces.

terized by the difficulty of pulling the object back. The parts does often get damaged when they are removed.

The flexibility of man can not be reached with automatic methods (today), but automatic assembly has the advantage in the long run with good and even quality. Several factors affect the possibility for automatic assembly. A few are mentioned above, like: position and orientation accuracy, tolerances, design for assembly, etc. All these aspects have to be considered in order to make real improvements to automatic assembly. In this thesis the industrial robot is equipped with a force/torque sensor to control the contact forces and thereby the relative positions of the assembled objects. This is one step towards more flexible automatic assembly.

3. Thesis

The basic problem in automatic assembly is the positioning accuracy. Force/torque control of industrial robots in contact operations has the ability to reduce position and orientation errors. A sensor model concept will simplify the use of force/torque sensors in robotic applications and an advanced robot controller will make it time and cost effective to develop such solutions.

3.1 Limitations

This work is focused on sensor based control of industrial robots. Other solutions to automatic assembly besides industrial robots have not been considered. The purpose of the work has been to improve the robot capabilities to manage assembly in a more efficient way. The force/torque feedback regulation has been considered in cartesian space and did not concern motor regulation in joint space.

4. Review of the literature

Ever since the childhood of modern industrial robotics (the early seventies), compliant motion has been considered a promising solution to many problems in robot control e.g. [Nevins, 1973], [Simunovic, 1975]. Familiar robot problems are positioning inaccuracies depending on limited resolution in the control system as well as tolerances and payload dependent deflections in the manipulator [Yao, 1989]. Even if the robot itself would be absolutely accurate, the environment can not always be treated as accordingly accurate. This justifies compliant motion to handle positioning inaccuracies in contact operations. Compliant motion can be considered a combination of force and velocity or position, where there is a defined relationship between position (distance) and force, when the end effector is in contact with the environment. The force position relationship can be compared with a spring and damper in parallel [Asada, 1985], [Kazeroni, 1986], see figure 5, where the environment or the robot deforms during contact. Compliant motion can be achieved in two different ways. The contact forces can modify positions due to compliance in the robot structure, in the servo or a flexible device in the end effector [Johansson, 1981], mounted appropriately. This is called passive compliance. The other possibility is called active compliance and is based on force and torque sensor feedback to the robot control system. [Whitney, 1977]. Of practical purposes, a combination of the two methods are often preferable.

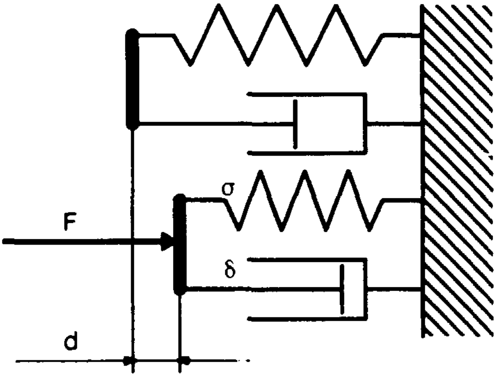

Figure 5. The force position relationship, Spring and damper in parallel.

$$F = \sigma \times d + \delta \times d$$

Compliant motion is applicable in many tasks to enhance the performance or quality aspects of contact operations. Mating of parts in assembly [Whitney, 1982], grinding, [Elbestrawi, 1991] drilling, programming [Lee, 1987] and contour tracking [De Shutter, 1988a], [Huang, 1987] are examples of contact dependent tasks. One of the most well investigated operations is the peg into hole assembly, among others, [Simunovic, 1975], [Wennström, 1988]. The analysis of force signatures in assembly processes [Fullmer, 1987], forces, torques and motions in four different stages of the assembly operation [Whitney, 1982] gives good basic knowledge when designing a compliant unit for assembly (Remote Center Compliance, RCC)[Drake, 1977], [Ericsson, 1979] or the computer algorithms for active force feedback compliance. Early implementations [Nevins, 1973], [Whitney, 1977] of force feedback consists of a desired trajectory which is modified by force feedback and a task dependent force control law. With this method, programming the task and designing the force feedback law is closely related, which might be time consuming and difficult for the average robot programmer.

A slightly different approach to enhance performance was investigated by [Van Brussel, 1978]. The solution was to configure the manipulator in such a way that each joint correlated to cartesian coordinate axes. With this configuration the forces in each translational joint was equal to the assembly forces. The relationship between measured force and the desired correction was simple and could be directly fed back to the respective joint controller. This did not apply exactly to the rotational joints because the lateral forces also caused torques see figure 6. The problem could be handled by specifying great stiffness in the wrist, causing lateral errors to be eliminated first. The benefit of this concept was twofold: good control performance (fast) and it was easy to specify the assembly strategy.

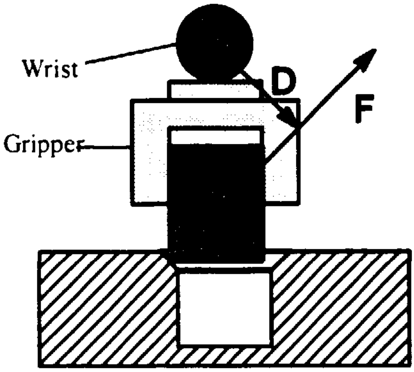

Figure 6. Assembly forces causing wrist torques. T = F x D

The next development of compliant motion specification technique, often called: "Hybrid force/position control" was developed by [Raibert, 1981], [Mason, 1981] and [Zhang, 1985]. What they had in common was the separation of force control specification from the control law implementation, making it easier for the user. All contact tasks can be divided into directions controlled by forces and directions controlled by positions, see figure 7. This means that a force controlled direction is in contact with some kind of surface, and therefore not free to move in that direction. The opposite is relevant for position

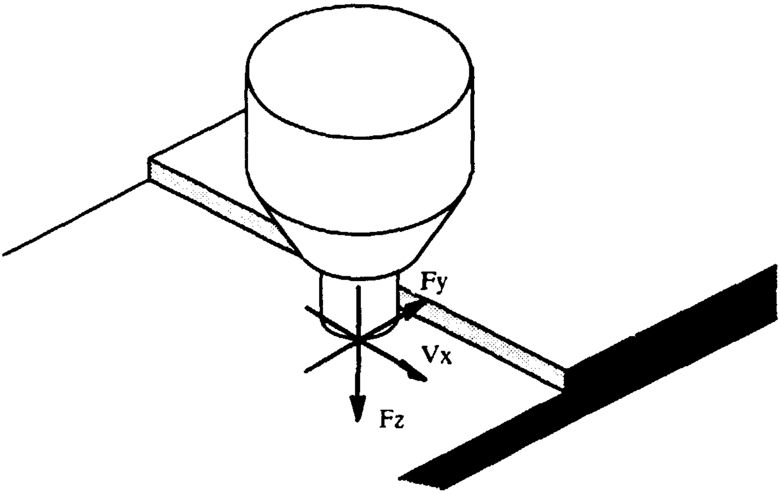

Figure 7. Hybrid control based on position in x–direction and forces in y– and z–direction.

controlled directions, no surface hinders motion. Friction is neglected. Mason also mentions a third control strategy: guarded move. It is a combination of position trajectory supervised by force for approach and touch of objects, avoiding excessive forces.

The hybrid position/force control concept has been used and refined by many researchers. To improve the practical usability, [De Schutter 1988a] added task termination conditions, tracking directions, feedforward velocity [appendix A]. These tools in combination with the hybrid control specification method separates programming from control and simplifies the user task. All specification assumes an ideal world while the control algorithm is robust to friction, finite stiffness and other disturbances [De Schutter 1988b].

Attempts with robust robot controllers has been made by among others [Fässler, 1990a], [Fässler, 1990b]. His approach was to use a dynamic model based on Kane's dynamical equations [Kane, 1983], [Kane, 1985] of the robot and assuming stiff contact with the environment. The stiff contact permits kinematic constraints to be included in the dynamical equations for the robot, one constraint for each "stiff direction". The solution is valid only for continuous contact which implicates difficulties for practical tasks where the contact directions are unknown in advance. Experiments with a three degree of freedom robot and one force controlled direction have been made. The results prove good robustness even when contact is partly lost.

In a future study [Seliger, 1991], the trend of increasing automation is supposed to be further intensified. He considers new manipulator materials to achieve better performance, multiple processor control systems and pipeline concept [appendix B] to improve updating frequency, as the most important fields in robotics research. Controlling compliant manipulators made by e.g. reinforced plastic, requires dynamical models of the manipulator. Several methods for dynamic control of manipulators have been studied [Hollerbach, 1980], [Silver, 1980], [Yang, 1986] are just a few examples. The inertial features of a dynamically controlled robot are very important for the resulting precision. A promising method to achieve those parameters is to use force and/or torque sensing to "calibrate" the inertial properties of the manipulator structure [An, 1985], [Baucent, 1989], [Mukerjee, 1989]. An et al estimated inertial information of robot links by measuring of joint torques while the manipulator was moving. An algorithm based on Newton Euler equations calculated mass, center of gravity and the moments of inertia for each link. Mukerje applied full force torque sensing in each joint. This allows complete inertial information for each link and reduces (eliminates) propagation errors across the manipulator.

The robot research is very often performed (applied) on special designed research robots with equally designed controllers. The major reason for this is the lack of commercial robots with open controller architectures and general programming languages. The requirements on robot programming languages differs in a wide range, from factory floor operators to robot researchers at universities and research centra's. A common viewpoint is that programming languages for robots should support the requirements for the most advanced users [Lozano-Peréz, 1982], [Taylor, 1982]. It is then possible to implement appropriate programming interfaces in the robot language itself. An interesting way to implement these ideas is to use a common programming language like C or Pascal and make software modules for the robot specific operations [Hayward, 1986], [Zebra].

5. The approach to a solution, introduction of the work and papers

To solve the problem of automatic assembly, all the factors mentioned in the problem description chapter have to be improved. This work is however focused on one of them, the problem of positioning inaccuracy. By using force/ torque sensor feedback in contact based processes, this problem can be solved.

When the author first got in contact with force/torque controlled robots, the approach to solving the adaptivity problem for industrial robots was according to a modification of Whitneys four state description of the insertion phase [Whitney, 1982], see figure 8. The force/torque control was carried out in four different algorithms, one for each state. Briefly described follows the algorithms used in each step:

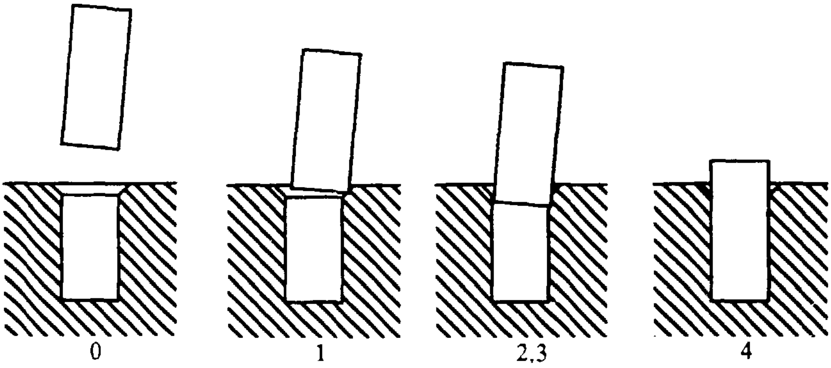

Figure 8. Modification of Whitneys four state description of the insertion operation

- state 0, no contact, search in approach direction for vertical force.
- state 1: one point contact, compensate for horizontal forces, move in the approach direction, repeat until state 2 occurs.
- state 2 and 3: two point contact, compensate for horizontal forces and horizontal torques, move in the approach direction, repeat until force limit for state four is reached.
- state 4: the final position is reached when the force in the opposite direction of the approach vector increases to a predefined limit.

For a more detailed description, refer to [Lundberg, 1986]. After studying this kind of strategy, it became evident that this approach would be very demanding in analysis and algorithm design. Practically all plausible contact based tasks would have to be analyzed and a control algorithm be designed. A more general and task independent algorithm would be a solution to this problem.

6. The sensor model concept

The author's work started with a deeper analysis of the insertion problem, which showed that a possible solution was a combination of state one and state two/three as described in the previous chapter. The overall algorithm to eliminate horizontal forces and horizontal torques, is valid from state 0 through state 3. The desire in state four, to reach a vertical contact force, can also be included in the "overall" algorithm. A logical consequence of the desire to reach a vertical contact force would be a robot motion in the opposite direction of the force. This force dependent motion can replace the constant motion in the old algorithm. When the desired force is reached and no other forces or torques are at hand, the goal position is probably reached as illustrated in figure 8, state 4. Unfortunately, this is no proof for the goal position being reached. An equivalent force will occur if the peg remains standing on the edge of the hole, see figure 9. To overcome the weakness of this simple stopping criteria. some more requirements can be added [appendix A]. In the above example, adding a distance requirement to the force/torque criteria will prove that the goal position is reached. Adding a timer can stop an unsuccessful insertion after a predefined elapsed time, indicating e.g. what happened in figure 9.

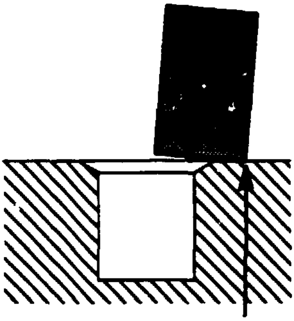

Figure 9. The peg is not inserted although the force requirements for stopping are fulfilled.

6.1 Task independent control

The analysis of the insertion problem indicated that a simpler and more general force/torque-based description was possible. In the beginning of the 1980's van Brussel conducted research on an insertion machine. The machine consisted of a cartesian arm and a 2 dof (degree of freedom) wrist. The joints were controlled with feedback of forces (arm) and torques (wrist) in a digital regulator [van Brussel, 1978]. The regulator principle for keeping forces near desired values, seemed very interesting and suitable for the force/torque-based algorithm outlined above. Transforming the motor regulation principle into hand space and a force-distance regulation relative to the wrist mounted sensor frame axes, gives independence of the manipulator design. Since the robot is controlled in base frame coordinates, wrist related coordinates from the regulation has to be translated into the base frame. The ABB robots were facilitated with a reltool function [ABB, 1986] permitting movements relative to the robot wrist. Because of limited access possibilities from peripheral computers, a new control package was implemented on an Apollo workstation, based on The ARAP (Asea Robot Application Protocol) (by that time Asea, later ABB) [Johansson, 1989]. The complete robot programs were now running on the Apollo workstation, eliminating logic and programs to be divided into two computers. A new "reltool" function was implemented in the Apollo based control package to maintain control relative to the wrist position, necessary for force/torque control. Input to the "reltool" function is the current gripper pose (position and orientation) and the incremental movement relative to the current pose.

6.2 Task specification with parameters

To simplify the analysis of contact operations to a matter of forces and torques, a sensor model concept was developed [appendix A]. The concept is based on parameters specifying desired force/torque intervals, see figure 10. The engineering process of preparing a contact based robot operation is transferred to an abstraction level of contacting surfaces/directions and or the magnitudes of the contact forces instead of developing control algorithms. All discussions of contact surfaces and directions are related to the end effector and its coordinate frame. The choice of force intervals instead of single values, is because of the stopping criteria. In the first version of the sensor model, in appendix A called the basic sensor model, the only stopping criteria was when all forces

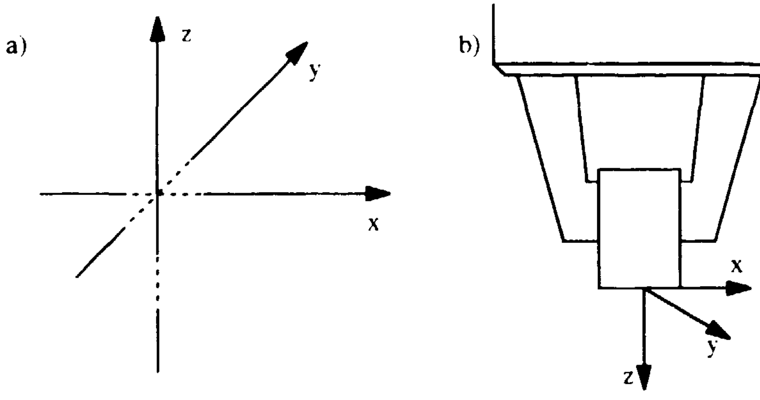

Figure 10. a) Force and torque frames, dotted lines indicating desired force or torque intervals. b) Sensor-fixed coordinate frame.

and torques were within desired intervals. Using a single value to describe the desired forces and torques, makes it practically impossible to reach the stop criteria satisfaction. If contact is wanted in a direction, say z, the proper force interval should be in the opposite direction, apart from zero, refer to the dotted part of the z-axis in figure 10a. When contact is not wanted, in terms of forces this is equal to keeping forces approximately zero, like in the x- and y-directions in figure 10a. The control strategy is to keep forces and torques within limits. This means controlling the robot in the opposite direction to the forces or torques. Another important parameter is the compliance in the robot and the contact environment. The compliance has to be defined for translations/ forces and for rotations/torques. The compliance parameter can be compared to the "proportional" parameter in a PID regulator. The compliance in the robot is unfortunately not isotropic. The compliance can vary quite considerably depending on arm and wrist configuration. This is a weakness in compliant control for standard robots. To overcome this drawback a compliant unit can be mounted at a suitable location e.g. between sensor and end effector. The compliant unit has to be weaker than the weakest "direction" in the wrist to get a more uniform compliance. Parameters for integration and derivation can of course also be implemented to handle sustaining errors and damping respectively. This was not considered necessary when the sensor model was designed, since the updating frequency of the robot was very low and the motion could be considered quasi static.

7. Proposal to new robot controller architecture

The experience from trying to interface sensors with a standard controller, mentioned in the previous section, showed that a control computer has to be open and expandable to facilitate such connections. Standard controllers have the disadvantage of being inflexible especially in their hardware. The architecture should be open for expansion of processor and memory power at different levels, to improve the possibilities of adding new routines and sensors etc. The software environment is more differentiated among robot brands. It is rather common to have application dedicated programming environments, that can only be used to make actual robot application programs. Other robots have more general purpose like high level programming languages, either for interpretation or compilation. The usefulness of these programming languages for research activities depends on how well developed the arithmetic and program control functions are. The level of the robot specific functions are also important. A good research environment has low level functions for joint control, and the higher levels of robot motions can be implemented in the programming language itself. To be really research friendly, the controller should allow different programming languages for different tasks. An example is to develop a rule based offline programming system in LISP programming language, because LISP is suitable for AI techniques. Another example is to implement low level interpolation routines in a compiling language or in assembler. This indicates an environment similar to what can be found in computer workstations; editor, compiler, linker, debugger, databases etc. Another important feature is the communications possibilities. To facilitate integration in factories (CIM) it is of great advantage if all computers and control systems are prepared for network connection. Network computing [Corbin, 1989] and "network file system" are basic features of the workstation concept and most computers have standard interfaces to different network techniques.

7.1 A general computer as platform

The proposed solution is to use a general (computer) workstation and expand the hardware with a Transputer based plug in board to handle heavy control systems calculations, see figure 11. The Transputer board is then interfaced to the servo control equipment, in this case the servos in the ABB S3 control system. This is possible thanks to special designed software from ABB that allows access to the S3 data bus via a double ported memory. The hardware is partly bought (Transputer board) and partly self wired (Transputer based memory interface) [Bergqvist, 1991].

A first version of the controller consists of an Apollo computer workstation, a Transputer equipped plug in board, a Transputer and double ported memory as interface to the servo computer of the ABB S3 controller, see figure 12 . The main computer (Apollo) is where the actual robot programs are executed.

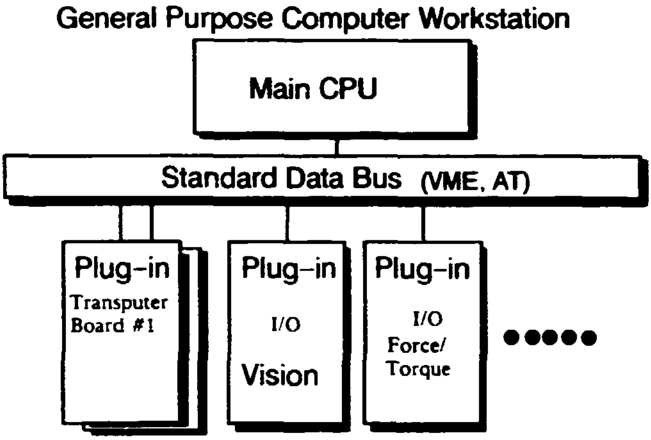

Figure 11. A general computer as a robot controller

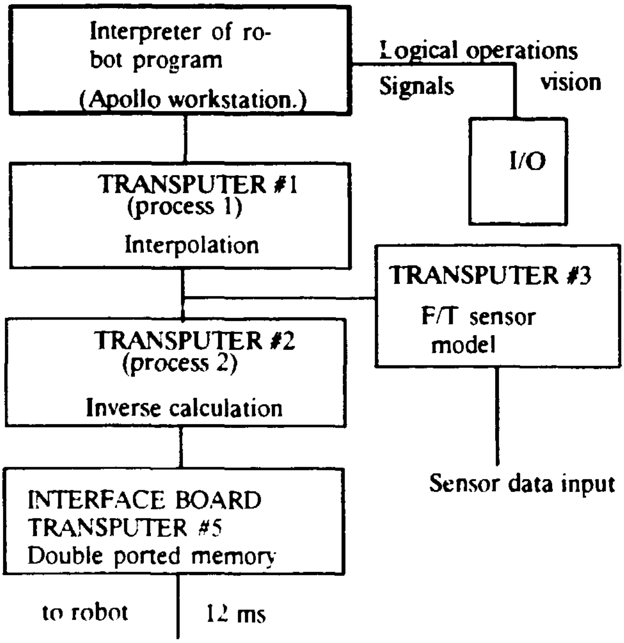

Figure 12. Hardware and software configuration for distributed and parallel processes of robot motion control.

This is on the standard program execution level for the workstation, why eg. a robot simulation system could be switched between simulation and control of the real robot. Different levels of programming interfaces can be implemented to meet the requirements of various categories of programmers. All robot specific commands are implemented as a set of modules which are linked to the robot application program or the execution environment (if the program is interpreted at a higher level). The robot specific software is either executed on the main processor or on the external Transputers. This is transparent from the users point of view.

7.2 Transputer architecture

The robot command "move_robot" is executed on the Transputer no 1, where the interpolation takes place. In the first version, the interpolation is of linear type [Herbertsson, 1990]. The call is parametric with parameters specifying start position (the current one is default), end position and end effector velocity. The path is interpolated into incremental movements of 12 ms each, see figure 13. Other interpolation routines are of course also possible. The interpolated intermediate positions are pipelined to Transputer no 2, where the inverse kinematic calculations are performed. The calculation method is an analytic solution to the ABB IRB 2000 inverse kinematics, which results in joint angles for all six joints. The joint angles are pipelined to Transputer no 5, which is the interface to the servo loop of the S3 controller. Each jont angle is here transformed to resolver increments on respective motor shaft and delivered to the servo controller. At this point the standard S3 servo takes care of the control of each motor to achieve the desired positions.

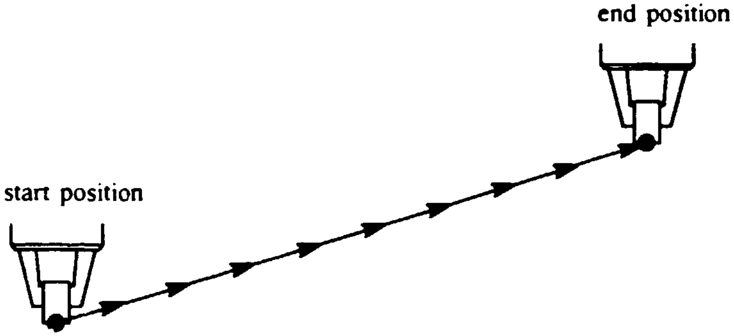

Figure 13. Linear interpolated point to point control. Intermediate positions reached every 12 milliseconds.

Most of the robot specific tasks can be performed across the interface on transputer no 5. The double ported memory is divided into segments with a wide variety of purposes, see figure 14.

Rel addr			Use	Source
$0	step_buff	54 bytes	Pos ref order data	Host
$36	lag_buff	48 bytes	Servo lag data	IRB
$66	posreg_r	48 bytes	Current pos.	IRB
$96	spare	46 bytes		
$C4	IO_buff	134 bytes	Digital and analog inp.	IRB
$14A	robt_data	128 bytes	General data	Host
$1CA	S3_data	128 bytes	General data	IRB
$24A	parm_buff	260 bytes	Parameter block data	IRB/Host
$34E	zero_pnt	62 bytes		
$38C	IO_event	48 bytes	Event def. digital in	Host
$3BC	text_buff	80 bytes	Textstring to display	IRB
$40C	not used			

Figure 14. Memory layout of the dual ported memory. [Lindholm, 1990]

The result of this connection will be the possibility to supply the robot servo loop with new joint (motor increment) values every 12 ms, allowing explicit sensor feedback as indicated in figure 12. The limitation to 12 ms updating cycle time is on the ABB S3 side of system. The Transputer-Apollo based controller has an estimated cycle time of less than 1 ms. The controller can be applied to any robot structure and brand by modifying the inverse kinematics and the motor interface (in this case it is a servo control interface).

8. Compensating gravity forces

Force/torque sensors for industrial robots can be used in many tasks. The tasks can be divided into two major categories: contact and non contact operations. Contact based operations, also called compliant motion, uses the contact forces to follow or search for surfaces, the other case concerns non contact which can be interesting when supervising gripper operations [Wennström, 1988]. In the non contact case the sensed feature is the mass of the gripped object. The mass gives an idea of wether an object is gripped, it is the correct object, detect dropping etc.

8.1 End effector mass and orientation

Both categories of tasks can be affected by the mass of the end effector. The most common way to eliminate the end effector mass is to use the reset bias function that is usually available on modern force/torque sensors. When the bias is reset, all the current forces are set to zero. After reset bias, only following changes in force/torques are detected, allowing relevant control be performed. For a task that doesn't require any rotations or at least no rotations perpendicular to the gravitation vector, no further actions than the reset bias need to be taken. The problem of gravity forces for changing end effector orientations is illustrated in figure 15. To handle this situation, the detected forces have to be adjusted for the gravity forces of the end effector. If the end effector mass is considerable and the task requires a limited number of orientations, then the bias can be reset each time a new orientation is needed. The major drawback is the time loss for each reset since the robot has to be at rest for some time (in the magnitude of a second) to eliminate vibrations. Force/torque

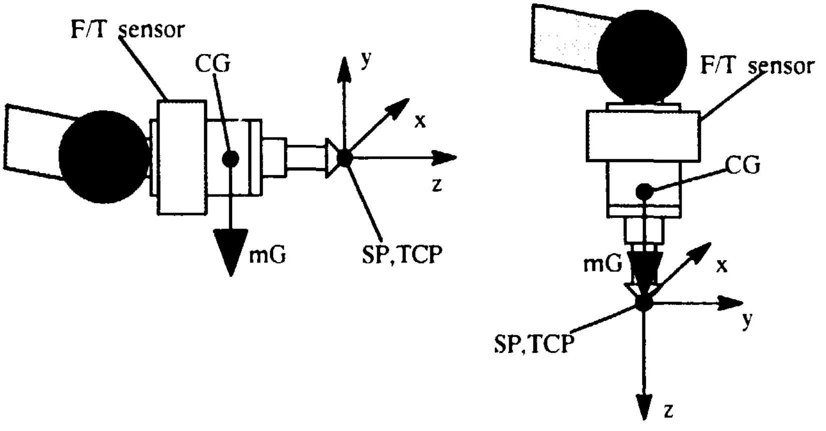

Figure 15. Varying gravity forces (mG) caused by different orientations.

controlled operations that include continuous orientation changes are only possible within small ranges of angle without any compensation for gravity forces. The range depends on the end effector mass and its distribution as well as the contact forces desired for the actual control operation. With continuous compensation for end effector mass, force/torque control is independent of orientation changes.

The end effector mass that has to be considered for compensation belongs first of all to the gripper (end effector) but also to some parts of the sensor, see figure 16. All parts of the sensor between the strain gauges and the gripper must be included in the end effector mass to compensate for. The end effector mass/(mass forces) has to be compared to the mass of the gripped object or the contact forces. If the forces applied by the end effector mass is infinite in comparison to the relevant forces, then there is no problem. Notice that if a contact operation is to be performed with an object in the gripper, then the object should be considered as a part of the end effector and similarly with its mass. (end effector mass = mass of end effector + mass of gripped object).

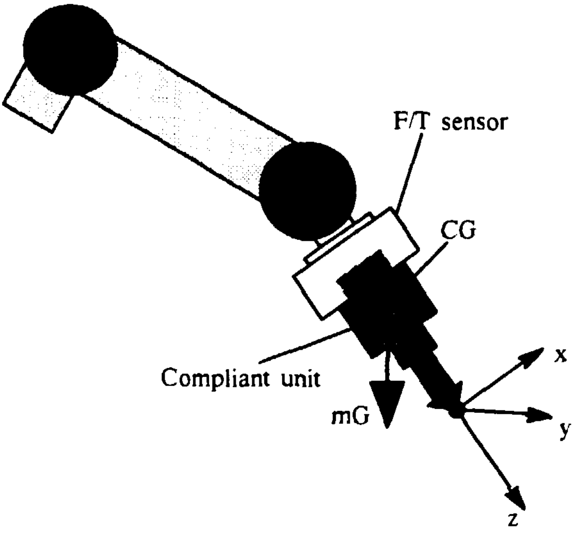

Figure 16. The mass of the end effector and a part of the sensor causes gravity forces. mG. (the shaded parts) ■

8.2 Gravitation and acceleration

The force contribution from the end effector mass comes from the acceleration of the end effector. According to Newtons second law:

$$F = m \times A$$

A complicating fact is that the acceleration consists of two basic parts: a static and a dynamic component, see figure 17. The static component is usually

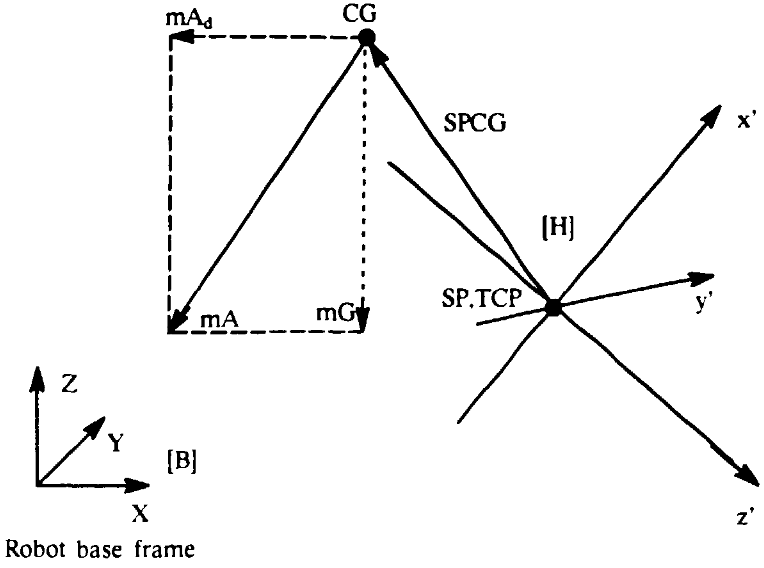

Figure 17. Acceleration vector (A) consisting of dynamic acceleration (A_d) and gravitation (G). [appendix C]

called gravitation and is always affecting the end effector and correspondingly the force/torque sensor output. The second component is acceleration that causes motion, either linear or angular. It can also be a result from angular motion (centrifugal force) or coriolis. The problem with the two different types of acceleration is that the gravity forces affects the sensor in the direction of the gravitation, while the other acceleration is given the end effector, by the sensor, and therefore corresponding forces will be detected in the opposite direction of the dynamic acceleration, see figure 18. A direct solution of measuring the acceleration of the end effector with accelerometers is therefore very difficult (impossible without external information). The gravitation can be traced by keeping record of the end effector orientation relative to the gravitation vector. This gives the gravitational acceleration in the sensor coordinate frame and from that also the force/torque contribution. The dynamic acceleration is more difficult to separate. If the robot is dynamically modelled and controlled, then it should be possible to get the dynamic acceleration from the robot controller. While waiting for dynamically controlled commercial robots another solution could be to equip the robot end effector with accelerometers. To separate the dynamic acceleration from the gravitation is difficult because the interesting accelerations usually lasts for say two or three seconds down to 0.1 second. These low frequencies are hard to get from an accelerometer without interference from the static gravitation, especially when rotating the

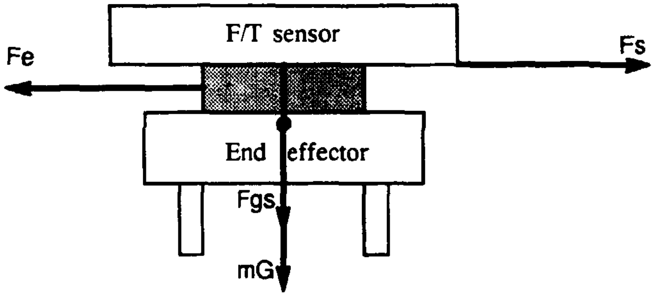

Figure 18. Newtons law of action and reaction. Fe in the direction of the end effector acceleration , Fs is the reaction force acting in the opposite direction on the sensor. The gravity force of the end effector (mG) and the reaction force (FGs) detected by the sensor are equal in direction and magnitude.

end effector. A conclusion is that it is very complicated to perform dynamic compensation in todays robots. The reasons are the complexity of the calculations and the difficulties to acquire valid acceleration data for the end effector. The fact that a lot of operations can be helped by just compensating for the gravitation, the major effort is put on that.

8.3 Three different complexity levels

Because of the two different natures of the end effector acceleration, three levels of compensation are developed.

- STATIC COMPENSATION
- SEMI DYNAMIC COMPENSATION
- DYNAMIC COMPENSATION

The gravity can be considered to be static as long as the robot installation is situated on the surface of the earth (at least fix relative to the field of gravity). The lowest level of complexity is the STATIC COMPENSATION which only adjusts sensor data for the gravity, refer to the mG-component in figure 17.

For a more accurate compensation, accelerations applied to the end effector should be considered. The compensation for dynamic accelerations can be divided into two complexity levels: complete dynamics and linear acceleration. Analyzing robot motion shows that movements to a high extent are linear, why compensation for linear accelerations is motivated. This is called SEMI DYNAMIC COMPENSATION and includes gravity compensation (STATIC COMPENSATION). Linear accelerations can be treated in similarity with gravity.

As for gravity, the only mass properties needed are the end effector mass and center of gravity [appendix C]. All calculations for gravity can be applied to linear acceleration with only slight modification.

Level three is called DYNAMIC COMPENSATION. It includes level one and a complete compensation for all dynamical effects caused by robot motion. The end effector model must include all inertial parameters, like mass, center of gravity, moments of inertia and products of inertia to facilitate dynamic adjustments of sensor data. The level of complexity for level three is considerably higher both for calculations and for acquiring acceleration data. Level three is not mathematically modelled in the paper [appendix C], just discussed.

9. Practical tests

For practical use of the sensor model, a software program was developed, called APPLICATIONS. The purpose of the program is to support a framework of necessary communication, initializations, robot and sensor specific functions,see figure 19. In this framework, robot applications can be implemented as subroutines called from a general application menu. For the purpose of force/torque control, the sensor model control algorithm can be called with application specific parameters that are stored in a parameter file. Intermediate robot positions can also be called from a file and commanded to the robot during the application program execution. Another program, called teach in, is used to teach robot positions and store into a position file as well as defining sensor model parameters for a specific application and store in a parameter file for later use in the application program. These two programs have been used to evaluate force/torque control and for different research related applications.

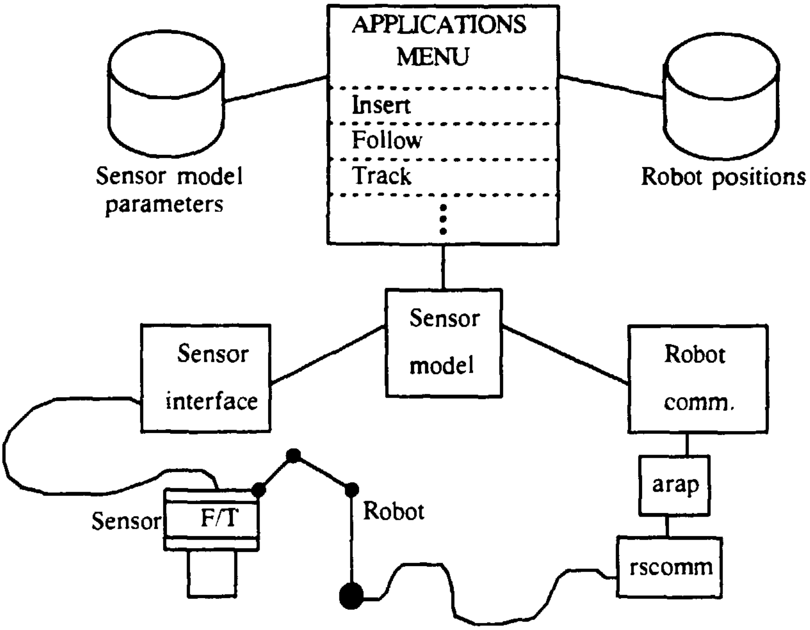

Figure 19. Structure of the sensor model application program.

9.1 Peg into hole insertion

The first test of the general task independent control algorithm was the well investigated peg into hole insertion problem. It was natural because of the previous experience of the four state algorithm, used for evaluation of active force/torque control [Lundberg, 1986] carried out at the department. In some of the different test cases, the physical setup was identical to what had been used earlier. This fact made it possible to compare the functionality between the two different approaches. The setup of the test equipment is described in figure 20. The diameter of the peg and hole was 25 mm with a clearance of 0.04 mm, the length/depth of the peg and hole was 30 mm. Trying to perform the insertion of the peg manually can be described as "a bit tricky". The force/torque controlled insertion was started from a position a few mm above the hole aligned within variously ± 1.5 degree and within ± 3 mm lateral positioning error, allowed by the chamfer, see figure 20. The insertion parameter set was principally (refer to appendix A):

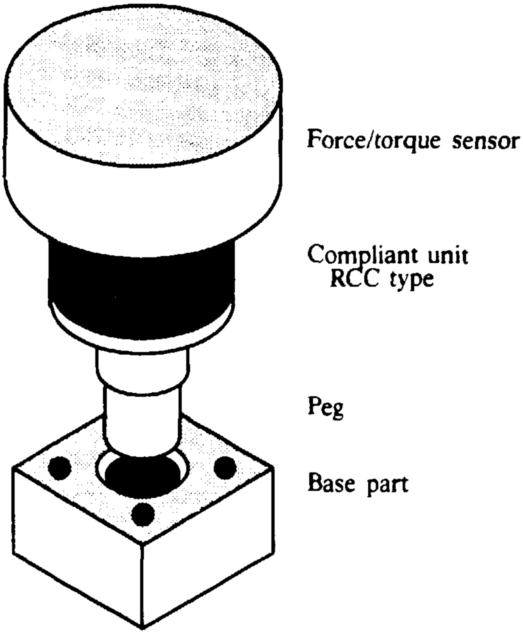

Figure 20. Test setup for peg into hole insertion.

upperlimit (2,2,-4,100,100,100) N, Nmm
lowerlimit (-2-2-8,-100,-100,-100) N, Nmm
maximum force = 15 N
maximum torque = 500 Nmm
translational compliance 10 N/mm
rotational compliance 2700 Nmm/degree
mainspeed = 0 mm/s
maindir = none

but the values were sometimes slightly changed for comparative reasons. The basic result was that the insertion could be performed with one control strategy as well as the four state algorithm used earlier. The stopping criteria was that all forces should be within their respective limits which usually occurred when the peg reached the bottom of the hole. Hitting outside the chamfer could also lead to termination of the insertion as the forces achieved their intervals. This could also happen with the four state algorithm. The solution to the stopping problem was to add other criteria's, such as: travelled distance, elapsed time and external signal. This was implemented in version two. The insertion speed was in relation to applied forces (parameters to the control law), larger forces = increased speed.

9.2 Mass compensation

The test of the mass compensation algorithm consisted of several stocastic orientations of a 1.7 kg end effector moving without contact. The mass compensation task is to adjust sensor data for all forces and torques resulting from end effector mass. Without environmental contact, the output should be zero in all directions independent of orientation. To find the mass properties of the end effector, a series of orientations were carried out, detecting forces and torques. The relations between forces, torques and orientations allowed mass and center of gravity to be calculated for the end effector. Using these calibrated data resulted in accurate adjustments. The errors from the compensation algorithm was approximately ± 2 percent of the end effector mass, in this case in the range of ± 0.4 N and ± 25 Nmm (the sensor accuracy is within ± 0.1N and ± 30 Nmm). Compared to contact forces in magnitude of 5 -15 N for this end effector, the calculation errors are negligible.

9.3 Following a template

The use of templates is very common in industry. They are used to support a variety of tasks, like cutting, carving, grinding, gluing etc. These are often manual tasks that could be done with a robot. The robot program can be made with a graphical offline programming system, but the robot path might not be correct due to inaccuracies in the robot structure, payload etc. A nice way to retrieve an accurate path in the actual robot coordinates would be to use a force/torque sensor in the robot wrist and follow the desired path along a template or a model of the object. If the same robot is used both for programming and execution, the path will be calibrated immediately if the payload and TCP (Tool Center Point) are equal. The idea was initialized by Saab aircraft division in Linköping, and an aircraft template was used in the experiment. In order to maintain the sensor x-direction in the tangent to the template edge, a special sensing device was designed, refer to figure 21. The sensing point and TCP was located in the central tip to which all forces and positions were related, refer to figure 21. The front tip was merely used to maintain the orientation along the template path. The principal parameter settings were: Keep contact with the underlying metal sheet and the template edge by issuing

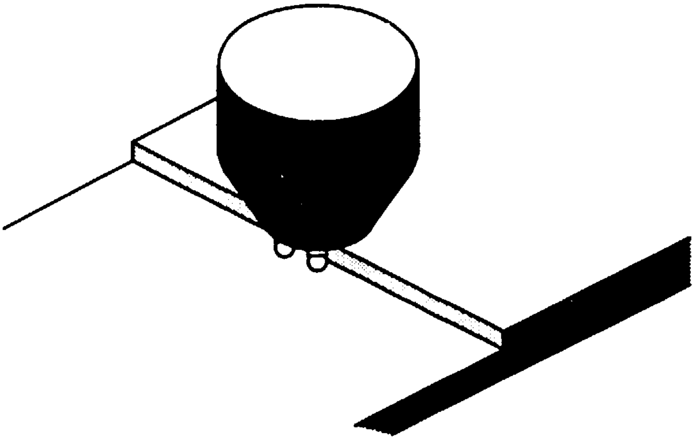

Figure 21. A special designed tool for template following. Two sensing tips in contact with the surfaces causes forces and torques to maintain the position and direction along the template.

forces in the negative z-direction and negative y-direction. The front tip can be kept in contact with the template by maintaining a minor torque around the negative z-axis. Note that the torque must be small in relation to the force in the negative y-direction not to loose contact of the central tip. The front tip can not apply force in the z-direction. The tangential motion can be defined independent of tangential forces, or be defined by the specification of a force in the negative x-direction that never occurs during the travel. The result is a constant tangential motion, only slightly affected by the friction forces. The test equipment was the usual ABB IRB1000, the Barry Wright force/torque sensor, an RCC compliant unit, special designed end effector and an aircraft wing panel template. The correctness of the recorded path can be calculated to ± 0.1mm in each direction. the calculation is based on measured forces and a compliance of 10 N/mm. The test was only 2.5 dimensional. The main problem to perform a full 3D path following is, besides the gravity forces (which can be handled), the mechanical device to detect all direction forces and transfer them to the sensor. Some solutions are being evaluated, but all seem to suffer some drawback. With other kind of sensors it is probably possible, but goes beyond the scope of this test.

9.4 Locating boiler connection holes

In a pre study to a EUREKA cooperation project, the division of Assembly Technology investigated the possibility to use force/torque sensors to locate holes. The participants in the pre study were Austria Email Austria, Österreichisches Forschungszentrum Austria, Esab AB Sweden and LiTH Sweden. The task of the robot cell was to assemble boiler connections to a number of holes in boilers of different sizes. The boiler could rotate in a horizontal fixture, why all assembly could be done from above. Two robots should cooperate, one welding robot and one assembly robot which first located the hole in question. The rough hole positions were either known in advance or estimated by vision. The assembly robot with the force/torque sensor should give an accurate position of the hole. The resulting position could then be used for assembly and welding. In the force/torque experiment, a simple conic tool was used, see figure 22. The search process started from a position 5 to 10 mm above the hole until a reliable contact force from the edge of the hole was established. The actual hole position could be calculated from the remaining forces and the compliance in the end effector together with the position retrieved by the robot. The search process took approximately 5 to 7 seconds until a resulting position was calculated. The accuracy was within ± 0.1 mm in the "horizontal directions", and within ± 0.2 mm for a vertical direction. The accuracy was established by moving the hole with an x- y- table and performing several tests in each position.

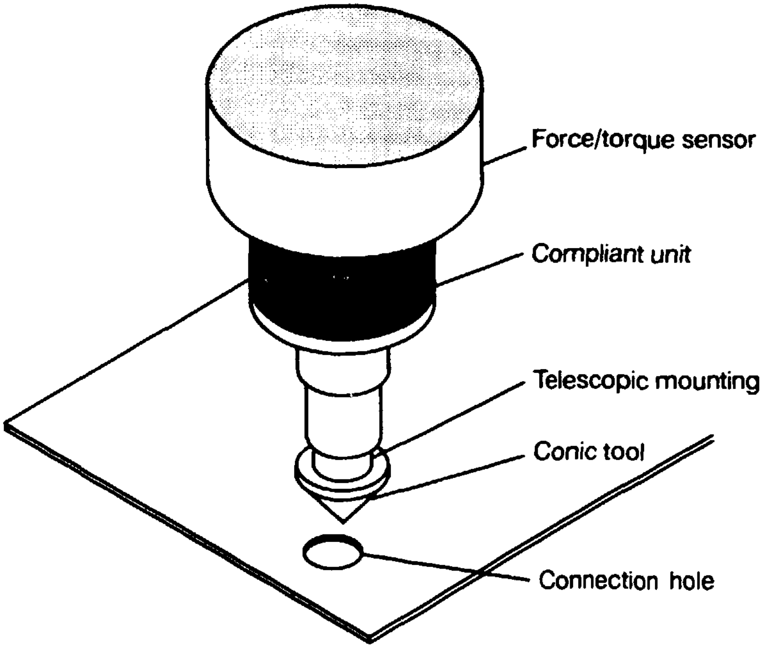

Figure 22. Test setup for the locating of boiler connections holes with a conic tool.

The tests presented here are among several other tests a way to evaluate the sensor model concept and the gravity compensation. The tests have been implemented in a software package, developed to serve as a test platform. The test software interface is just a simple hierarchical menu based program, with environment for defining and testing sensor model parameters. The definition phase is usually an iterative trial and refining procedure. The sensor model evaluation has proved that it is easy to specify parameters to achieve the desired behavior. An experienced user can achieve a good behavior in the very first trial, but a few iterations are common. A good example is the location of boiler connection holes, where the complete task was specified and tested in one hour. The gravity compensation allows reorientations during force/torque controlled operations. It is thereby a good contribution to the flexibility of such operations. The mentioned tests have not been executed on the new open controller concept, which is still under implementation.

10. Results and conclusions

The presented work has resulted in three internationally published papers with a common interest in improving robotic contact operations. The basic problem in automatic assembly is the position and orientation inaccuracy. All modifications to a system might cause inaccurate positions. This problem is especially prominent in flexible assembly systems where exchanges of assembly setups are frequent. By tests, see e.g. chapter 9.1, and in literature e.g. [Van Brussel, 1978], [Johansson, 1981] it has been proved that active and/or passive compliance can be a solution to the inaccuracy problem. A remark to active compliance is that it is too slow to be used in real applications. The proposed solution is to use active sensor support for adaptations of bad positions in the adjustment period of a new installation and just supervision and error correction in the daily work. Supervision takes no additional time, why the time requirements are fulfilled.

In order to improve the user friendliness of advanced sensors for robotcontrol, a sensor model concept was developed, chapter 6, [appendix A]. The concept is based on a task independent control algorithm. The behavior of the robot is specified by a set of parameters instead of designing a new algorithm for each task. Important parameters are: desired forces and torques, compliance and stopping criteria. The stopping criteria is a logical combination of stopping requirements. The stopping criteria has been difficult to implement in Pascal, but easy in the interpreting AML/2 language.

Practical tests have proved that new tasks can be specified with minor effort using the defined parameters. A good example is the location of boiler connection holes in chapter 9.4. However, good knowledge about the parameters as well as the sensor and coordinate frames is required. To meet the need for simple programming with sensor support, high level sensor functions should be introduced. Sample high level functions are: insert, track, search, follow etc [Johansson, 1992].

A drawback is that the sensor model becomes slower in complex situations, than a special designed algorithm. This is because the sensor model has to be stopped and reconfigured for each sub task. So far, the implemented control algorithm has unfortunately slow access to the manipulator controller, which reduces execution speed. This problem will be solved (the control will be *closer* to real time) in the new controller concept in chapter 7 and [appendix B].

The end effector mass is a limitation of the spatial working area for force/torque controlled robots. The orientation must be locked to avoid variations in the gravity forces. To overcome this limitation and error source, a method for gravity compensation is developed [appendix C]. An automatic calibration procedure gives an assurance of accurate mass properties of the end effector. The deviation from the theoretical output is small. A typical value of the errors caused by inaccurate mass properties, orientation data and the computations, is less than ± 2% of the end effector gravity force. Eliminating gravity forces gives greater freedom to apply force/torque sensors in a broad spectrum of tasks and reduces error sources.

The problems experienced from the incorporation of external sensors into commercial robot controllers emerged into a concept for an open controller architecture [appendix B]. The hardware is based on a general computer workstation equipped with Transputers in pipeline for interpolation, inverse kinematics and servo control. The architecture is open for modifications and expansions both in hardware and software, which simplifies the incorporation of sensors. The computer workstation concept has a good potential for the integration of machines and office in the factory, due to mature network facilities.

The addressed problem with inaccurate positions in the assembly process has been solved using a task independent control algorithm for a force/torque sensor. The first statement in the thesis (chapter 3) is verified by the implementation of the sensor model (chapter 6) [appendix A], and the fact that practical tests have been successful (chapter 9).

The intention with the sensor model was to simplify the use of force/torque sensor support in robotic applications. The second statement in the thesis is verified by practical tests (chapter 9) and by a comparison of the amount of work and knowledge required for specifying a task with parameters to the sensor model (chapter 6) [appendix A] and designing a new task specific algorithm. Combining the sensor model with a method for compensation of end effector gravity forces (chapter 8) [appendix C] simplifies the use of force/torque sensor support even more. The sensor model is also a good platform for the implementation of high level generic sensor functions [Johansson, 1992].

The value of the proposed controller architecture (chapter 7) [appendix B] can so far not be verified in amount of time and money according to the thesis. However, it is reasonable to assume that the flexible software and hardware architecture will make sensor integration easier and thereby less expensive. It is also possible to interact with the "real time" loop of the controller, why tough time requirements can be met.

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Appendix

This part contains the three papers on which this thesis is based. The papers have been reformatted to be more readable and fit this size and style. The content is however unchanged.

Appendix A:

General Parametric Sensor Model With External Communication Possibilities, Presented at the 20:th ISIR in Tokyo.

Appendix B:

Towards Common Infrastructure for Advanced Manufacturing Control Systems, Presented at the fifth ICAR in Pisa.

Appendix C:

An Efficient Mass Compensation Method for Force/Torque Control in Robotics, Presented at the Fourth World Conference on Robotics Research in Pittsburg.