Chapter 7

General Conclusion

Robot manipulators offer a lot of promising applications in industrial activities. However, this potential has not been fully exploited yet. Assembly is a typical example of manipulation tasks where the robot motions are constrained during the task execution. When dealing with complicated objects or in case of a highly uncertain environment, a single robot arm may fail to accomplish the assigned tasks.

In this case a multi robot system may offer a solution. In order to optimally exploit the capabilities of a multi robot system, the following issues have to be considered:

- How to assign a common task to a multi robot system; in this thesis the case of two cooperating robot arms is analyzed. The task has to be executed in a coordinated manner, and to be realized automatically. In addition, the task has to be formulated in a simple way.

- What are the characteristics of a multi robot system that make them superior to a single robot system. Furthermore, how to exploit these characteristics in a suitable way.

- How to design and implement a cooperative control to realize the coordinated motion for a multi robot system, which is based on the two previous issues.

Below the contributions of this thesis in light of these issues are summarized.

Task specification for multi robot system.

A new task specification for compliant motion of two cooperating robots has been designed. These specifications are an extension of an existing robot compliant motion specification for a single robot arm.

Two specifications are introduced. The first is called the *move synchronously* command. This is based on the ordinary compliant motion; but automatically extracts feedforward information gathered from the counter-part robot. In particular, task frame velocities are transformed from one robot to other robot. This specification realizes only coordinated motion between two robots. As a result, this formulation is not very flexible, in the sense that the robot programmer has to define accurately the motions of the two robots in advance.

The second specification is called the *move cooperatively* command. This is also based on the ordinary compliant motion specification, but exploits the redundant properties of the multi robot system. This specification allows the cooperating robots to utilize all degrees of freedom they possess. As a result, the robot programmer can impose some important constraints to the mechanism, i.e. avoiding singular positions or finding suitable configurations.

Using this specification, the controller uses information from both robots continuously, and drives the robots to a better configuration. This offers a solution for performing difficult tasks for robotic systems in general.

Control strategy by means of redundant properties.

Utilizing redundancy in two cooperating robots contributes markedly to the increased flexibility, and the simplicity of compliant motion specification. The task is defined in a similar way as in the existing compliant motion specification. Only a small modification has been introduced.

Characteristics and implementation of redundancy in a multi robot system have been studied in great detail. The main issues addressed are the following:

- Treating and analyzing a multi robot system as a kinematically redundant manipulator, as there are twelve degrees of freedom for performing a task having six degrees of freedom. This gives more dexterity for the system to accomplish difficult tasks.

- The task of the multi robot system as one single mechanism is divided into levels of priority, i.e. high priority and low priority tasks. The high priority task must be realized at any time, while the low priority task is only executed whenever possible using the remaining degrees of freedom.
- In this implementation, the high priority is assigned to the relative position and orientation of the two end-effectors. In other words, the contact point between tool and the object to be worked on, has to be kept constant. The lower priority is used to minimize objective functions that always keep the contact point within the common work space. At the same time, it avoids singular configurations in Cartesian space as well as in joint space level.

Implementation results.

Both specifications for two cooperating robots are implemented on two industrial KUKA robots. The cooperative tasks are read by the tasks interpreters, and sent to the robot controllers. The control scheme called *Comrade* is a rather general scheme which allows different control algorithms to be implemented.

Some simulation results have been shown; they have been verified experimentally. These results demonstrate the effectiveness of the new specification for two cooperating robot arm, especially the use of redundant properties.

The technique presented here has some potentials for various applications. In the car industries, tracking of an unknown contour by two cooperating robots can be used for automatic doors gluing. In nuclear environments, this technique will certainly become important for automatical dismantling processes, e.g. for cutting operations where one robot holds an object, while the other operates a cutting tool.

Suggestions for Further Developments

Although the control strategy developed in this thesis has been successfully implemented on two industrial robots, the performance is still far from being optimal. In fact, the performance of the whole system depends on various aspects, e.g. force control parameters, speed of the redundant control, ability of the system to avoid collisions, the ability of the high level control for finding the best path of the two robots, and so on.

In this thesis, only one aspect is worked out, i.e. the implementation of a control strategy based on the redundancy of a two robot system. And even this control loop runs very slowly; it runs only at 10 Hz. This strongly limits the performance of the system. On the other hand, in all experiments the starting configuration is always free from a collision between the tool and object to be worked on.

To get maximum performance with this control strategy, some developments have to be done in the future. Here, the two most urgent improvements are suggested:

- speeding up the redundant control.
- implementing the automatic collision avoidance.

• Speeding Up The Redundant Control.

It is really necessary to speed up the redundant control loops up to the speed of the main control loops if it is possible. The main reason why these control loops run very slowly is that software virtual channels are used between the transputers for transferring information. This in fact, seems to be only suitable for data communication between processes within one transputer, as these channels utilize the transputer data bus. The transfer is apparently fast enough without disturbing the robot control loops.

Possible solutions to avoid this problem are:

- Devoting one separate process in each robot transputer (TPT - 0 and TPT - 2) which runs for instance at 50 Hz. This process continuously keeps the last status of its own robot, and is ready to send it to the redundant controller. It also keeps requesting the new updated configuration from the third transputer (TMB012). For communication, hardware communications can be implemented, instead of the virtual channel facilities [94]. In this case, the link number has to be specified explicitly.

- To control two cooperating robots using a redundant control strategy, three transputer nodes in one physical board would be excellent. Software virtual channels can still be implemented exactly the same as used for controlling a single robot arm. As the channels utilize the transputer data bus, it would be not too time critical for transferring data between the transputer nodes.

- The other possible solution is using a different communication technique, which in fact has been successfully implemented on the LiAS, which stands for Leuven intelligent Autonomous System. It is a mobile robot where the controller utilizes eight different transputers. The main controller runs under a programming system, the so called *Virtuoso* which stands for Virtual Single Processor Programming System [95]. This system offers some advantages in programming a transputer system. The programmer can send information from one task (in one transputer) to another task (in other transputer) without having to care about the links between the transputer nodes. Data can be sent at a link speed of 20 Mbit/sec which is a very high rate. Implementation of this feature for controlling two cooperating robots will significantly improve the overall performance of the system.

- **Collision Avoidance for Two Cooperating Robots.**

Another important subject to optimize the performance of the control strategy developed here is the necessity to implement a collision avoidance technique, i.e a strategy for finding the safest path for the robots to move from one point to another. This strategy involves path planning for the robot motion, and it has to be implemented on-line, i.e. during the main task execution.

In the manipulation tasks demonstrated here, the two robots always start executing the task from given safe initial positions. From a flexibility point of view, this is not the best solution. Instead, the two robots must be able to start from any arbitrary configuration. If collision may occur while approaching the start configuration, it has to be detected in advance, and the current path has to be modified immediately. So the starting configuration can be reached safely. This action has to be done on-line based on the current position of the robots.

Path planning for multi robot systems has gained an increasing attention, as this planning is one of the fundamental requirements for task oriented robot programming. Some good examples are given in [14, 41, 45, 84, 85] for solving problems of collision among moving objects in general.

Bibliography

[1] Ahmad S., Guo H., *Dynamic Coordination of Dual-Arm Robotics Systems with Joint Flexibility*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.332-337.

[2] Ahmad S., Luo S., *Coordinated Motion Control of Multiple Robotic Devices for Welding and Redundancy Coordination through Constrained Optimization in Cartesian Space*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.963-968.

[3] Albert T.E., Soloway D.I., *Force Control of A Multi-Arm Robot System*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.1490-1496.

[4] An C. H., Hollerbach J.M. *Dynamic Stability Issues in Force Control of Manipulators*, Proceedings of the IEEE Conference on Robotics and Automation, 1987, pp.890-896.

[5] An C. H., Hollerbach J.M. *Kinematic Stability Issues in Force Control of Manipulators*, Proceedings of the IEEE Conference on Robotics and Automation, 1987, pp.897-903.

[6] Arthaya B., *A Study of Robotic Deburring: Normal Compensation of Robot Deflection to Improve Path Accuracy*, Master Thesis, Mech. Eng. Department, K.U. Leuven, 1990.

[7] Arthaya B., De Schutter J., *Experiments on Co-operating Robot Arms*, Proceedings of the Int. Workshop on Fuzzy Logic and Intelligent Technologies in Nuclear Science (FLINS'94), 1994, Mol, Belgium, pp.144-149.

[8] Arthaya B., De Schutter J., *Cooperative Control for Multi Robot Arms*, Proceedings of the Pacific Conference on Manufacturing, Jakarta, Indonesia, 1994, pp.469-476.

[9] Arthaya B., De Schutter J., *Experiments on Force Controlled Deburring*, Proceedings of the Pacific Conference on Manufacturing, Jakarta, Indonesia, 1994, pp.498-506.

[10] Arthaya B., De Schutter J., *Utilizing Redundancy in Multi Robot Arm Systems*, Proceedings of the 4th Int. Conference on Intelligent and Autonomous Systems, Karlsruhe, Germany, 1995, pp.374 - 380.

[11] Arthaya B., De Schutter J., *Two Cooperating Robots, an example of Kinematically Redundant Manipulator*, Proceedings of the 7th Conference of The Indonesian Aerospace Students in Europe, Manchaster, U.K., 1995, pp.E1-E8.

[12] Asada H., Ogawa K., *On the Dynamic Analysis of A Manipulator and Its End Effector Interacting With The Environment*, Proceedings of the IEEE Conference on Robotics and Automation, 1987, pp.751-757.

[13] Bruyninckx H. De Schutter J., *Model Based Specification and Control of Compliant Motion*, Tutorial presented at the IEEE Conf. on Robotics and Automation, Nice, France, 1992.

[14] Cheng X., *On-line Collision-free Path Planning for Service and Assembly Tasks by a Two-Arm Robot*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nagoya, Japan, 1995, pp.1523-1528.

[15] Chiacchio P., Chiaverini S., Sciavicco L. Sicilliano B., *Closed Loop Inverse Kinematics Scheme for Constrained Redundant Manipulators with Task Space Augmentation and Task Priority Strategy*, The Int. Journal of Robotics Research, Vol.10, No.4, 1991, pp.410-425.

[16] Chiacchio P., Chiaverini S., Sicilliano B., *Dexterous Reconfiguration of a Two-Arm Robot System*, Proceedings of Int. Conference on Control '91, Edinburg, UK, 1991, pp.347-351.

[17] Chiacchio P., Chiaverini S., Sicilliano B., *Cooperative Control Scheme for Multiple Robot Manipulator Systems*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.2218-2223.

[18] Chiacchio P., Chiaverini S., Sicilliano B., *Task-Oriented Kinematic Control of Two Cooperative 6-DOF Manipulators*, Proceedings of 1993 American Control Conference, San Fransisco, CA, 1993.

[19] Craig J.J., Raibert M.H., *A Systematic Method of Hybrid Position/Force Control of a Manipulators*, Proceedings of the IEEE Int. Conference on Robotics and Automation, 1979, pp.446-451.

[20] Craig J.J., *Introduction to Robotics. Mechanics and Control*, Addison-Wesley Publishing Company Inc., 1986.

[21] Crauwels G., Georis O., *Krachtsturing en Taakspecificatie bij Samenwerkende Robots*, (in Dutch), Ir. Thesis, Mech. Eng. Department, K.U. Leuven, 1993.

[22] Dauchez P. et.al, *Task Modeling and Force Control for A Two-Arm Robot*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Sacramento, CA, 1991, pp.1702-1707.

[23] Dauchez P. et.al, *Force Control Experiments with A Two-Arms Robot*, Journal of Intelligent and Robotic System 5, 1992, pp.253-269.

[24] Dellinger W.F., Anderson J.N., *Interactive Force Dynamics of Two Robotic Manipulators Grasping a Non-Rigid Object*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.2205-2210.

[25] Demey S., Dutré S., Persoons W., Van De Poel P., Witvrouw W., De Schutter, J., Van Brussel H., *Model Based and Sensor Based Programming of Compliant Motion Tasks*, Proceedings of 24th Int. Symposium on Industrial Robots, 1993, Tokyo, Japan, pp.393-400.

[26] Demey S., De Schutter J, *Fast and High-Quality Planar Contour Following in the Presence of Large Position Uncertainties*, Proceedings of the IEEE International Conference on Robotics and Automation, 1995, Nagoya, Japan, pp. 2096-2101.

[27] Deniard J., Faillot J.L., Swevers J., Torfs D., *Design and Implementation of an Antivibration Robot Control Software*, Chapter in Vibration Control of Flexible Servo Mechanisms, Research Report ESPRIT, Project 1561, SACODY, Vol.1, Chap.8, Springer-Verlag, 1994, pp.169-187.

[28] De Schutter J., *Compliant Robot Motion: Task Formulation and Control*, PhD Thesis, Mech. Eng. Department, K.U. Leuven, 1986.

[29] De Schutter J., *A Study of Active Compliant Motion Control Methods for Rigid Manipulators Based On A Generic Scheme*, Proceedings of the IEEE Conference on Robotics and Automation, 1987, pp.1060-1065.

[30] De Schutter J., Van Brussel H., *Compliant Robot Motion I. A Formalism for Specifying Compliant Motion Tasks*, Int. Journal of Robotics Research, vol 7/4, 1988, pp.3-17.

[31] De Schutter J., Van Brussel H., *Compliant Robot Motion II. A Control Approach Based on External Control Loops*, Int. Journal of Robotics Research, vol 7/4, 1988, pp.18-33.

[32] De Schutter J., *Improved Force Control Laws for Advanced Tracking Applications*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.1497-1502.

[33] De Schutter J., Van de Poel P., Witvrouw W., Bruyninckx H., Demey S., Dutré S., *An Environment for Experimental Compliant Robot Motion*, Tutorial presented at the IEEE Int. Conference on Robotics and Automation, Atlanta, 1993, pp.1-15.

[34] Dorf R.C. et.al., *Concise International Encyclopedia of Robotics: Application and Automation*, John Wiley & Sons, Inc., 1990.

[35] Doty K.L., *A Theory of Generalized Inverses Applied to Robotics*, The Int. Journal of Robotics Research, Vol.12, No.1, 1993, pp.1-19.

[36] Duffy J., *Analysis of Mechanics and Robot Manipulators*, London: Edward Arnold, 1980.

[37] Eppinger S.D., Seering W.P., *Introduction to Dynamic Models for Robot Force Control*, IEEE Control System Magazine, 1987, pp.48-52.

[38] Eppinger S.D., Seering W.P., *Understanding Bandwidth Limitations in Robot Force Control*, Proceedings of the IEEE Conference on Robotics and Automation, 1987, pp.904-909.

[39] Eppinger S.D., Seering W.P., *Three Dynamic Problems in Robot Force Control*, IEEE Transactions on Robotics and Automation, Vol.8, No.6, 1992, pp.751-758.

[40] Featherstone R., *Position and Velocity Transformations Between Robot End-Effector Coordinates and Joint Angles*, The Int. Journal of Robotics Research, Vol.2, No.2, 1983, pp.35-45.

[41] Freund E., Hoyer H., *Pathfinding In Multi-Robot Systems: Solution and Applications*, Proceedings of the IEEE Conference on Robotics and Automation, San Fransisco, CA, 1986, pp.103-111.

[42] Fujii S., Kurono S., *Coordinated Computer Control of A Pair of Manipulators*, 4th World Congress on The Theory of Machines and Mechanisms, Newcastle upon Tyne, UK, 1975, pp.411-417.

[43] Ghosal A., Desa S., *Dynamical Resolution Redundancy for Robot Manipulators*, Transactions of the ASME, Vol.115, 1993, pp.592-598.

[44] Hayati S., *Hybrid Position/Force Control of Multi-Arm Cooperating Robots*, Proceedings of the IEEE Conference on Robotics and Automation, San Fransisco, CA, 1986, pp.82-89.

[45] Hayward V., Aubry S., Foisy A., Ghallab Y., *Efficient Collision Prediction Among Many Moving Objects*, The Int. Journal of Robotics Research, Vol.14, No.2, 1995, pp.129-143.

[46] Heyndrickx L., Ruiz M., *Controle van Samenwerkende Robots*, (in Dutch), Ir. Thesis, Mech. Eng. Department, K.U. Leuven, 1994.

[47] Hsu P., Su S., *Coordinated Control of Multiple Manipulator Systems: Experimental Results*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.2199-2204.

[48] Ishida T., *Force Control in Coordination of Two Arms*, Proceedings of the 5th Int. Joint Conference on Artificial Intelligent, 1977, pp.717-722.

[49] Kazerooni H., *Automated Robotic Deburring*, American Control Conference, Minnepolis, Minnesota, June, 1987.

[50] Khatib O., *Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation*, the IEEE Journal on Robotics and Automation, Vol.RA-3(1), 1987, pp.43-53.

[51] Kim K.I., Zheng Y.F., *Two Strategies of Position and Force Control for Industrial Robots Handling a Single Object*, Robotics and Autonomous Systems, Vol.5, 1989, pp.395-403.

[52] Kramer B., Shim S.S., *Development of a System for Robotic Deburring*, Robotic and Computer Integrated Manufacturing, Vol.7, No.3/4, 1990, pp 291-295.

[53] Kumar V., *A Compact Inverse Velocity Solution for Redundant Robots*, The Int. Journal of Robotics Research, Vol.12, No.1, 1993, pp.45-54.

[54] Lim J., D. H. Chyung., *Cooperative Control of Two Manipulators*, IFAC Control Science and Technology for Development, Beijing, 1985, pp.275-278.

[55] Lim J., D. H. Chyung., *A Control Scheme for Two Cooperating Robot Arms*, IEEE Control Systems Magazine, 1987, pp.65-68.

[56] Low K.H., Dubey R.N., *A Comparative Study of Generalized Coordinates for Solving the Inverse-Kinematics Problem of 6R Robot Manipulator*, The Int. Journal of Robotics Research, Vol.5, No.4, 1986, pp.69-88.

[57] Lozano-Perez T., *Robot Programming*, Proceedings of the IEEE, 71/7, 1983, pp.821-840.

[58] Luh J.Y.S., Zheng Y.F., *An Interactively Hierarchical Control Scheme for Two Coordinating industrial Robots*, Proceedings of 25th Conference on Decision and Control, Athene, Greece, 1986, pp.1265-1266.

[59] Mason M.T., *Compliance and Force Control for Computer Controlled Manipulators*, Master Thesis, Department of Electrical Engineering and Computer Science, M.I.T, May 1978.

[60] Mason M.T., *Compliance and Force Control for Computer Controlled Manipulators*, IEEE Trans. Systems, Man, and Cybernetics, SMC-11(6), 1981, pp.418-432.

[61] Nakamura Y., *Advanced Robotics, Redundancy and Optimization*, Addison-Wesley Publishing Company Inc., 1991.

[62] Payandeh S., Goldenberg A.A., *A Robust Force Controller: Theory and Experiments*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Sacramento, CA., 1991, pp.36-41.

[63] Persoons W., *Fast Algorithms for Real-time Forward and Inverse Robot Kinematics. A Case Study On the KUKA IR 160/60 Robot*, Mech. Eng. Department, Div. PMA, K.U. Leuven, Internal Report 93R20, 1993.

[64] Pittelkau M., *Adaptive Load-sharing Force Control for Two-arm Manipulators*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.498-503.

[65] Pohl E.D., Lipkin H., *Complex Robotic Inverse Kinematic Solution*, Journal of Mechanical Design, Vol.115, 1993, pp.509-514.

[66] Pueh L.H., *Motions With Minimal Joint Torques for Redundant Manipulators*, Journal of Mechanical Design, Vol.115, 1993, pp.599-603.

[67] Qian H.P., De Schutter J., *The Role of Damping and Low Pass Filtering in the Stability of Discrete Time Implemented Robot Force Control*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.1368-1373

[68] Qian H.P., De Schutter J.,*Introducing Active Linear and Nonlinear Damping to Enable Stable High Gain Force Control in Case of Stiff Contact*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.1374-1379

[69] Raibert M.H., Craig J.J., *Hybrid Position Force Control of Manipulators*, ASME Journal Dyn. Syst., Meas. and Control, 102, 1981, pp.126-133.

[70] Ramadorai A.K. et.al, *Task Definition, Decoupling and Redundancy Resolution by Nonlinear Feedback in Multi-Robot Object Handling*, Proceedings of the 1992 IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.467-474.

[71] Reynaerts D., *Control Methods and Actuation Technology for Whole-Hand Dexterous Manipulation*, PhD. Thesis, Mech. Eng. Department, K.U.Leuven, 1994.

[72] Schneider S.A, Cannon,Jr R.H., *Experimental Object-Level Strategic Control with Cooperating Manipulators*, the Int. Journal of Robotics Research, Vol.12, No. 4, pp.338-350.

[73] Suh I.H., Shin K.G., *Coordination of Dual Robot Arms Using Kinematic Redundancy*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.504-509.

[74] Tao J.M., Luh J.Y.S., *Position and Force Control for Two Coordinating Robots*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Sacramento, Calif., 1991, pp.176-181.

[75] Tarn T.J., Bejczy A.K., Yun X., *Coordination Control of Two Robot Arms*, Proceedings of IEEE Int. Conference on Robotics and Automation, San Fransisco, CA, 1986, pp.1193-1202.

[76] Tarn T.J., Bejczy A.K., Yun X., *Dynamic Coordination of Two Robot Arms*, Proceedings of 25th Conference on Decision and Control, Athene, Greece, 1986, pp.1267-1270.

[77] Torfs D., De Schutter J., *A New Control Scheme for a Flexible Robot Driven by a Velocity Controlled Actuator*, Proceedings of 23th Int. Symposium on Industrial Robots, 1992, Barcelona, Spain, pp.314-319.

[78] Torfs D., De Schutter J., *Tuning of an Add-on Flexible Mode Controller for a Robot, Driven by a Velocity Controlled Actuator*, Presented at the SY.RO.CO 94, Capri, Italy, 19-21 September 1994.

[79] Uchiyama M., Kanamori Y., *Quadratic Programming for Dextrous Dual-Arm Manipulation*, Robotics, Mechanics and Manufac. Systems, Elsevier Science Publishers B.V., 1993, pp.367-372.

[80] Uchiyama M., Dauchez P., *A Symmetric Hybrid Position/Force Control Scheme for the Coordination of Two Robots*, Proceedings of IEEE Int. Conference on Robotics and Automation, Philadelphia, PA, 1988, pp.350-356.

[81] Uchiyama M., Yamashita T., *Adaptive Load Sharing for Hybrid Controlled Two Cooperative Manipulators*, Proceedings of IEEE Int. Conference on Robotics and Automation, Sacramento, CA, 1991, pp.986-991.

[82] Van Aken L., *Robot Motions in Free Space: Task Specification and Trajectory Planning*, PhD Thesis, Mech. Eng. Department, K.U. Leuven, 1987.

[83] Van Brussel K., Surinx D., *Aktieve Lokalisatie van Vlakke Voorwerpen* (in Dutch), Ir. Thesis, Mech. Eng. Department, K.U. Leuven, 1994.

[84] Warren C.W., *Global Path Planning Using Artificial Potential Fields*, Proceedings of the IEEE Int. Conference on Robotics and Automation, 1989, pp 316-321.

[85] Warren C.W., *Multiple Robot Path Coordination Using Artificial Potential Fields*, Proceedings of the IEEE Int. Conference on Robotics and Automation, 1990, pp.500-505.

[86] Whitney D.E., *Force Feedback Control of Manipulator Fine Motions*, ASME Journal Dyn. Syst., Meas. and Control 99(2), 1977 pp.91-97.

[87] Whitney D.E., *Historical Perspective and State of the Art in Robot Force Control*, The Int. Journal of Robotic Research, Vol.6, No.1, 1987, pp.3-13.

[88] Witvrouw, W., Van De Poel P., Bruyninckx, H., De Schutter, J., *ROSI: a Task Specification and Simulation Tool for Force Sensor Based Robot Control*, Proceedings of 24th Int. Symposium on Industrial Robots, 1993, Tokyo, Japan, pp.385-392.

[89] Yang B.H, Asada H., *Hybrid Linguistic/Numeric of Deburring Robots Based on Human Skills*, Proceedings of the IEEE Int. Conference on Robotics and Automation, Nice, France, 1992, pp.1467-1474.

[90] Zheng Y.F., Luh J.Y.S., *Constrained Relations Between Two Coordinated Industrial Robots*, Proceedings of 1985 Conference on Intelligent System and Machines, Rochester, MI, 1982, pp.118-123.

[91] Zheng Y.F., Luh J.Y.S., *Control of Two Coordinated Robots in Motion*, Proceedings of 24th IEEE Conference on Decision and Control, Ft. Lauderdale, FL, 1985, pp.1761-1765.

[92] *KUKA Handbuch*, RO IR 160/60, Dok. 103.08.4 d, KUKA Schweißanlagen + Roboter GmbH, Germany.

[93] *KUKA Handbuch*, RO IR 361/18/15.8, Dok. 559.08.8 d, KUKA Schweißanlagen + Roboter GmbH, Germany.

[94] *Transputer Toolset*, Vol.1-2, Documentation Logical Systems, Vol. 1-2, U.S.A., 1992.

[95] *Virtuoso, Virtual Single Processor Programming System*, User Manual, Intelligent System International, Belgium, 1992.