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Impressum
Published by

Publisher: Rector of the Ilmenau University of Technology
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff

Editor: Marketing Department (Phone: +49 3677 69-2520)
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Editorial Deadline: 20. August 2010

Implementation: Ilmenau University of Technology
Felix Böckelmann
Philipp Schmidt

USB-Flash-Version.

Publishing House: Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

Production: CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

Order trough: Marketing Department (+49 3677 69-2520)
Andrea Schneider (conferences@tu-ilmenau.de)

ISBN: 978-3-938843-53-6 (USB-Flash Version)

Online-Version:

Publisher: Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=16739

COOPERATION OF ROBOTS UNDER FORCE/TORQUE CONTROL

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ABSTRACT

Force/torque control of robot manipulators has been quite intensively investigated during the last decades and it becomes more and more important concerning manufacturing tasks. However, in the case of cooperation between industrial robots, they are predominantly position controlled. This article deals with the cooperation of robots based on force/torque control. For the purpose of demonstration a challenging task will be selected – the assembly of a screw fitting by two force/torque controlled robot arms. This experiment will be performed using hybrid position/force control. For the implementation two industrials robots with its original controllers have been used. This fact reduces the possibilities of force/torque control with respect to controller structures and parameters.

Index Terms— Robot cooperation, force/torque control, hybrid position/force control, force/torque sensor

1. INTRODUCTION

The research field of robot force control has been investigated quite extensive during the last decades, [1], [2], [3]. Force control can be used expediently when the manipulator is in contact with an unknown environment. From the contact forces and torques measured by force/torque sensor suitable commands have to be computed to actuate the robot. In contrast to the research activities, most of the industrial robots work position controlled, however, force control becomes more and more important concerning manufacturing task, like polishing and deburring. Another interesting application of robot force control is the cooperation between multiple robots which will be presented in this paper.

In general, force control algorithms can be divided into implicit [4], [5], [6] and explicit force control, [7]. In this paper only explicit force control will be regarded, because in contrast to implicit force control or impedance control the desired contact forces can be directly set which is important for the application chosen in this work. A lot of publications assume that the force controller can act on the joint torque or motor current level of the robot actuated system. In this case the dynamic model of the robot can used to decouple and linearize the system, [8]. Unfortunately, it is often not possible to modify the controller of an industrial robot to get access to the motor currents. In this presentation the standard robot controller is kept unchanged. This kind of robot force control can be denoted as the external force control, [9].

For a scenario of cooperation between multiple robots under force/torque control we choose the following example application: Two industrial robots have to mount together a screw fitting using hybrid position/force control as can be seen in Fig. 1.

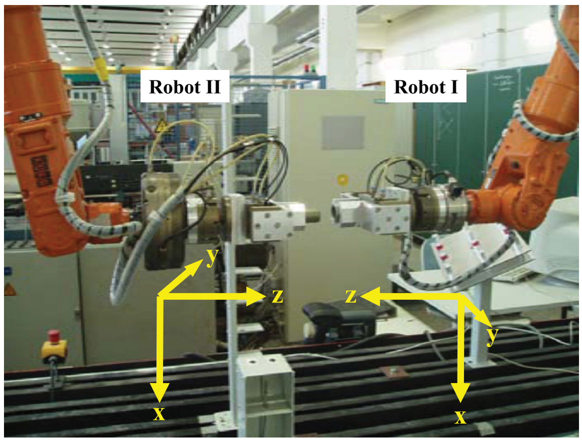

Fig. 1. Scenario of screwing and orientation of robot tool frames.

This paper is organized as follows: In the next section the robot system used for the experiment will be described in detail. Then in section 3 the controller structure will be selected and the particular controllers will be parameterized. In section 4 some results of the experiments will be presented and in the last section the short conclusion will be given.

2. EXPERIMENTAL SETUP

2.1. Robots

The robot system used for cooperation of two robots under force/torque control consist of two KUKA KR6/2 manipulators. They are six axes articulated robot arms with a nominal payload of 6 kg on the flange and additional payload of 10 kg on the forearm. Each robot is controlled by its own KUKA Robot Controller KRC2 based on an industrial PC. At the PC the real time operating system VxWorks runs together with Windows. VxWorks is used for real time tasks and Windows for program design and visualization. User robot applications can be programmed using KUKA Robot Language (KRL) which has all features of common robot programming languages.

Both robots are equipped with force/torque sensor. On the wrist of Robot I a stiff sensor is mounted (SCHUNK FT-Delta). Its measuring range is 660 N/ 60 Nm for forces and torques, respectively. This sensor is connected to the robot controller by a special ISA-DAQ board. The contact forces and torques of Robot II were measured by the SCHUNK Force Torque Compliance (FTC) Sensor connected via CAN-BUS / DEVICE-NET to the robot controller. In contrast to stiff F/T sensors with high stiffness based on strain gauge measurement, this sensor includes a compliance. The deformations caused by forces/torques are measured by PSD devices. The measuring range of Sensor II is $150\ N\ (300\ N)$ for forces and $7\ Nm\ (15\ Nm)$ for torques in x and y direction (z direction) respectively. Additionally, the sensors are protected by pneumatic robot load limiters. For assembling and handling objects two-finger parallel grippers were used.

2.2. Robot Force Control

As already mentioned, most of the commercial robot controllers permit the user access to the joint torques or motor currents. The ordinary way to initiate robot motions using a commercial robot controller is by instructions for joint interpolation, linear or circular interpolation. The motion commands are sent to the trajectory generator which creates the time series of desired positions, velocities and accelerations. Motions generated in that way are smooth motions without jerks. They are suitable for industrial applications, e.g., handling or assembling tasks. However, they are not applicable in any kind of sensor guided robot motion, such as force/torque control.

Robot controller KRC2 has the advantage to admit real time access to the robot motion variables, which is very important to force control. This feature is realized by the so called Robot Sensor Interface RSI. It is an additional module which realizes real time signal processing and the access to the position control loops. There are two possibilities to implement robot force control.

Using RSI directly, an individual controller structure can be generated, [10], [11]. It consists of RSI objects with different functionalities, e.g. providing the measured values of force/torque sensor, signal processing (proportional element, integrator, derivative element, summation, etc.) and taking influence on robot motion by position correction in Cartesian or joint space. This method is very flexible and challenging according to the implementation.

Another way to realize force/torque control with the described robot system is the KUKA Force Torque Control Technology Package (FTCtrl). With this software a very easy implementation of force control applications using a Windows dialog is possible. The disadvantage is that FTCtrl gives rather limited possibilities in program design. In spite of this, FTCtrl will be used for the demonstration of force controlled cooperation of robots.

2.3. Communication and Periphery

The synchronization between the two robots is very important for a successful realization of the planned task. In the standard configuration of the robot controller KRC2 it includes field bus of type CAN-BUS / DEVICE-NET. Each robot controller acts as master on its own bus and is able to address its peripheral devices, e.g. digital input and output devices, pneumatic valves, etc. The digital inputs and outputs are realized with a BECKHOFF field bus node and the corresponding modules. In the same way the communication between the two separate networks is implemented. A pair of serial data exchange modules is used to build up the communication between Robot I and Robot II. In each direction 32 Bit can be transmitted which is sufficient for our application.

3. CONTROLLER CONFIGURATION FOR SCREWING

3.1. Hybrid Position/Force Control

The method of hybrid position/force control was proposed by Raibert & Craig, [12]. Mason [13] defines natural and artificial constrains which separate the force controlled directions from the position controlled directions. The set of natural constrains is orthogonal to the set of artificial constrains. Generally, hybrid position/force control is implemented by means of explicit control. Fig. 2 shows its basic structure.

The current values of forces/torques and position / orientation in Cartesian space are expressed by vectors $\vec{F}$ and $\vec{X}$:

$$\begin{aligned} \vec{F} &= \begin{bmatrix} F_x & F_y & F_z & M_a & M_b & M_c \end{bmatrix}^T \\ \vec{X} &= \begin{bmatrix} x & y & z & a & b & c \end{bmatrix}^T \end{aligned} \tag{1}$$

In the sense of KUKA Robot Language KRL a, b and c are the Euler angles around the z, y and x-axis respectively, to describes the orientation of the tool frame. In the same way M_a, M_b and M_c represent the interaction torques around these axes. The desired values of forces

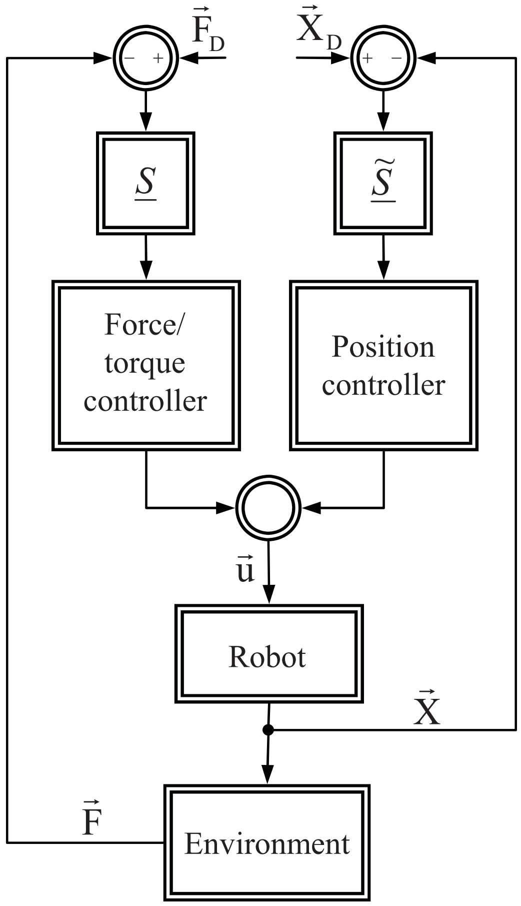

Fig. 2. Basic scheme of hybrid position/force control.

and position are expressed by vectors $\vec{F}_D$ and $\vec{X}_D$. The diagonal matrix $\underline{S}$ defines the force/torque controlled directions. In the case the value of the corresponding element on the main diagonal is 1 force control is activated. Otherwise this value is set to 0. In the same way matrix $\underline{\tilde{S}}$ selects the position controlled directions, hence:

$$\underline{\tilde{S}} = \underline{I} - \underline{S} \tag{2}$$

The outputs of force and position controller are merged to the generalized vector $\vec{u}$ to influence the robot motion.

3.2. Controller Parameterization

For the particular task of assembly the following steps are necessary:

- Select the force controlled degrees of freedom in matrix $\underline{S}$,
- Adjust the controller gains,
- Determine the desired values of forces and torques,
- Define suitable break conditions.

Using KUKA's Force Torque Control (FTCtrl) this tasks can be performed using the comfortable Windows application FTCtrl Config.

3.2.1. Find contact between nut and thread bold

First of all the contact between the nut and the thread bolt has to found. The thread bolt is hold by Robot II. Robot I brings the nut close to the thread bolt. Because its position is not exactly known the nut is attached to the thread bolt by force control. The force/torque controlled directions with respect to tool frame are selected by matrix $\underline{S}_{11}$:

$$\begin{aligned} \underline{S}_{11} &= diag(1,1,1,0,0,0) \\ &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \end{aligned} \tag{3}$$

Matrix $\underline{S}_{11}$ enables force control along x, y and z-axis. The torque components around these axes are disabled, which means the orientation of the tool frame will be kept constant by position control. The vector of desired force (torque) values is chosen as follows:

$$\vec{F}_{11_D} = \begin{bmatrix} 0 & 0 & -6 & 0 & 0 & 0 \end{bmatrix}^T \tag{4}$$

Forces are expressed in physical unit $[N]$ and torques in $[Nm]$. If F_z reaches F_{z_D}, this subtask will be finished.

After attaching the nut to the thread bolt, the nut is rotated counter-clockwise relative to the thread bolt. The rotation around the tool frame z-axis of Robot I is performed in torque control mode, therefore the desired value of M_a and the break condition have been chosen. Selection matrix and vector of desired forces/torques are denoted as $\underline{S}_{12}$ and $\vec{F}_{12_D}$ for this subtask:

$$\begin{aligned} \underline{S}_{12} &= diag(1,1,1,1,0,0) \\ \vec{F}_{12_D} &= \begin{bmatrix} 0 & 0 & -8 & 6 & 0 & 0 \end{bmatrix}^T \end{aligned} \tag{5}$$

The break condition is set to $-180\ deg$ for Euler angle a.

Some facts about the controller parameterization will be mentioned on the end of this section.

The screwing task will be executed in three steps. In the first one only Robot I works. It performs the first revolution of screwing. Robot II is deactivated for this period. The selected values of force/torque control are as follows.

$$\begin{aligned} \underline{S}_{13} &= diag(1,1,1,1,0,0) \\ \vec{F}_{13_D} &= \begin{bmatrix} 0 & 0 & -10 & -6 & 0 & 0 \end{bmatrix}^T \end{aligned} \tag{6}$$

This subtask will be finished by achieving the break condition $a > 310\ deg$ which means the rotational angle around the z-axis of tool frame. Subsequently, the gripper of Robot I is opened and moved to the initial orientation for joint-screwing.

The screwing of the two robots together will be performed also under force/torque control. For this purpose both robots work in hybrid position/force control mode. The selection matrices and vectors of desired forces/torques are denoted by $\underline{S}_{14}$, $\vec{F}_{14_D}$, $\underline{S}_{24}$ and $\vec{F}_{24_D}$ for Robot I and Robot II, respectively:

$$\begin{aligned} \underline{S}_{14} &= diag(0,0,1,1,0,0) \\ \vec{F}_{14_D} &= \left[\begin{array}{cccccc} 0 & 0 & -2 & -7 & 0 & 0 \end{array} \right]^T \\ \underline{S}_{24} &= diag(1,1,0,1,0,0) \\ \vec{F}_{24_D} &= \left[\begin{array}{cccccc} 0 & 0 & 0 & -7 & 0 & 0 \end{array} \right]^T \end{aligned} \qquad (7)$$

The hybrid position force/control mode will by deactivated by two break conditions:

- The desired value of the screwing torque M_{a_D} is reached,
- The robot motions around tool frame z-axis is limited to $180\ deg$.

In the first case the screwing task has been finished and the mounted workpiece can be put down by Robot II. In the case that force control has been canceled by orientation angle limit, the screwing process has to be continued. For this purpose both robots move back to initial orientation for screwing after Robot I opens its gripper. If both robots reached the initial orientation and the gripper is closed again, screwing can be continued according to (7).

3.2.2. Controller structure and gains

For the particular tasks the force controllers have to be adjusted. Because in our example the KUKA Force Torque Control technology package (FTCtrl) is used, the possibilities concerning controller parameterization are limited. The controller structure is fixed and can not be modified. The controller gains can be adjusted for each direction by linguistic variables which represents environment stiffness and control speed.

In the case that the stiffness of the environment is known it can be set directly in the physical units $[N]$ or $[Nm]$ for each translational or rotational degree of freedoms, respectively. Another way is the choice of some predefined values like "very soft", "soft", "medium", "stiff" or "very stiff". The parameter "control speed" can by only set to "slow", "medium", "fast" or "very fast". As an example, Fig. 3 show the settings in the controller configuration utility FTCtrlConfig of Robot I in subtask 4.

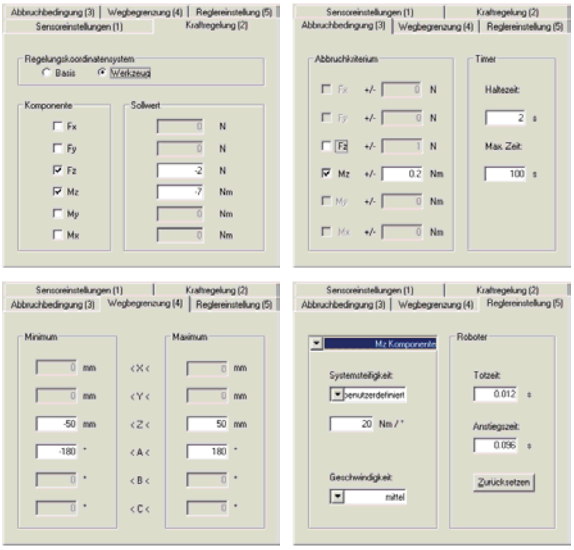

Fig. 3. Controller settings of Robot I in subtask 4.

The performance and stability of the closed loop control depends on these two parameters. Here are some examples: If the parameter of environment stiffness is set to "stiff" or "very stiff" and the speed parameter is set to "slow" the transient behavior of contact forces and torques will be very slow. On the other side the system will be away from the stability boundary. If we choose the controller parameters as "soft" and "fast" the transient behavior will be faster. However, it may occur that the whole system becomes unstable in presence of stiff environment. Table 1 shows the selected parameters for each individual task and robot.

4. EXPERIMENTAL RESULTS

For both manipulators robot programs was developed and implemented into the corresponding robot controllers to perform the assembling task of screwing. The robot programs include handling of workpieces, communication and synchronization between the robot controllers, parameterization and execution of the force/torque control algorithms from the FTCtrl technology package, and error handling.

At the beginning Robot I grips the nut and Robot II takes thread bolt and bring the workpieces to start position for mounting. Then Robot I tries to establish the contact between the nut and the thread bolt in force control mode (task 1). This situation can be seen as the well known peg-in-hole problem, [14]. The arising contact forces with respect to the tool frame of Robot I can be seen in Fig. 4. There is very strong overshoot of F_z when the workpieces get in contact because the environment is stiff. Reducing this overshoot will result in a slower approaching velocity which is not preferable.

In task 2 and task 3 Robot I screws alone while

Table 1. Controller parameters

Degree of freedom	Environment stiffness	Control speed
Robot I, task 1		
F_x	100 N/mm	fast
F_y	100 N/mm	fast
F_z	130 N/mm	slow
Robot I, task 2		
F_x	100 N/mm	fast
F_y	100 N/mm	fast
F_z	medium	slow
M_a	soft	fast
Robot I, task 3		
F_x	100 N/mm	fast
F_y	100 N/mm	fast
F_z	stiff	slow
M_a	soft	fast
Robot I, task 4		
F_z	170 N/mm	slow
M_a	20 Nm/deg	medium
Robot II, task 4		
F_x	medium	fast
F_y	medium	fast
M_a	20 Nm/deg	medium

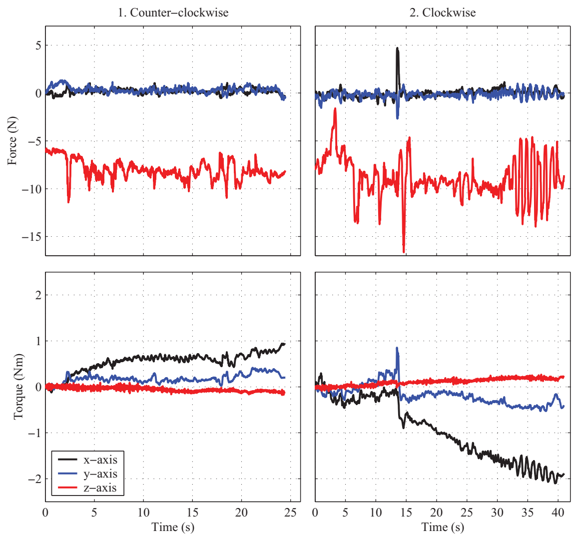

Fig. 5. Forces/torques during task 2 and task 3.

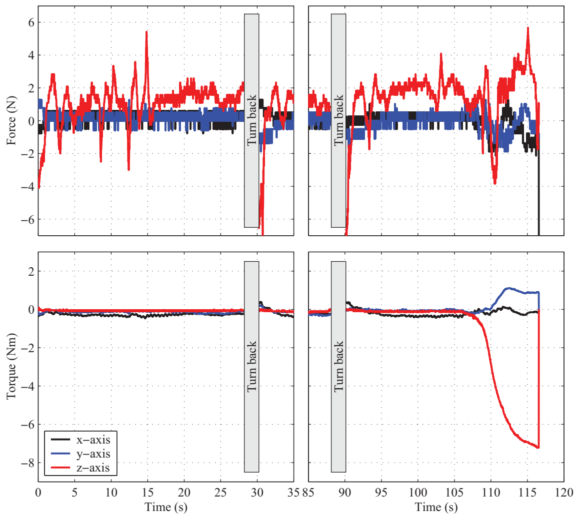

Fig. 6. Forces/torques during cooperative screwing.

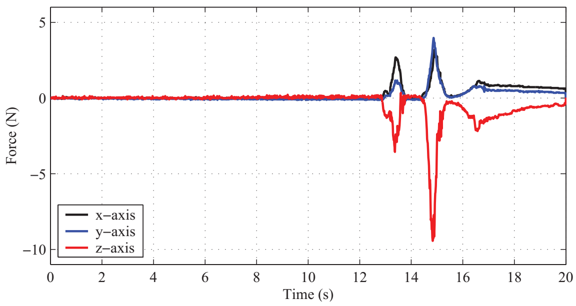

Fig. 4. Forces during contact detection.

Robot II stands still and its force/torque sensor is locked. First screwing is performed counter-clockwise to find the thread. After the break condition of task 2 is reached the nut will be screwed clockwise. The plots of measured forces and torques are shown in Fig 5.

For completing the screw fitting in task 4 both robots work together. Because of the limitation of the working range of joint 6, both manipulators have to turn back with open gripper before the desired mounting torque is reached. Forces and torques during the robot-robot cooperation can be seen in Fig 6 with respect to tool frame of Robot II.

Finally some snapshots of the assembling task can be found in Fig. 7.

5. CONCLUSION

In this paper the successful realization of force controlled screwing was presented. This task was chosen for a challenging example of cooperation between multiple robots under force/torque control. For the implementation a suitable robot work cell has to be configured consisting of two industrial robots equipped with force/torque sensors. Force/torque control was than implemented using the functionality of KUKA's FTCtrl technology package. For every particular subtask the parameterization of hybrid control has been performed. Results in terms of plots of contact forces and torques during the cooperation of two robots were presented.

Further efforts may be the improvement of force / torque control concerning e.g. assembling time. For this purpose it seems to be possible to replace the algo-

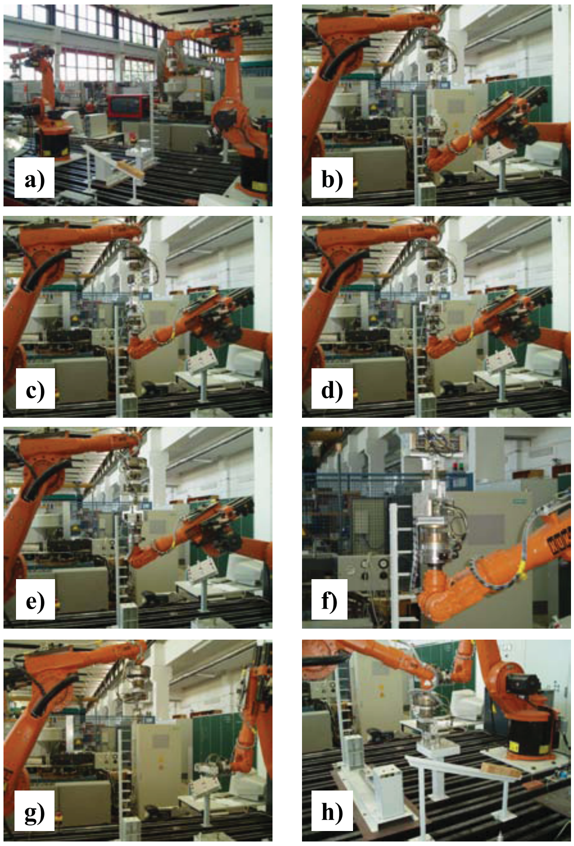

Fig. 7. Assembling of nut and thread bolt by Robot-robot collaboration under force/torque control.

rithms of FTCtrl by self developed controls strategies realized by RSI programming. This was already presented in [15] in context to force control of a single manipulator arm. It may be perspective to assign these algorithms also to force control of cooperating robots.

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