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Compliance Control with Dual-Arm Humanoid Robots: Design, Planning and Programming

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***Abstract*— A widespread application of impedance control in dual-arm robotic systems is still a challenging problem. One of limitations is the absence of a widely-accepted framework for the synthesis of the impedance control parameters that ensure stability of both contact transition and interaction processes and guarantee desired contact performance. The next critical problem relates planning and programming of complex impedance controlled bimanual operations. The proposed new design, planning and programming framework provides efficient and flexible algorithms and tools which considerably facilitate future dual-arm robot applications in complex assembly tasks. The initial testing with new Workerbot dual-arm system demonstrates applicability and feasibility of the proposed framework.**

I. Introduction

Recent industrial development of dual-arm robots (e.g. Motoman SDA-series, DLR-KUKA Justin etc.) has considerably leveraged interest of researchers and users for this new class of robotic systems. The main advantages and benefits of dual arm-robots over single arm systems are obvious: *multitasking* (the arms can operate independently or synchronously performing complex bimanual assembly tasks), *cost saving* (a dual-arm robot can replace at least two convenient robots, as well as expensive fixture and regrasping devices) and *space saving* (a dual-arm robot requires smaller operating space). There are, however, several practical difficulties in understanding, controlling, planning and programming of dual-arm operations.

A realistic approach to dual-arm planning is based on mimicking human operations. The human dual-arm operations (Fig. 1) may be divided in *non-coordinated* (each arm realizes an independent motion) and *coordinated* (with temporary and spatial coordination of arm movements). The coordinated motion can be further split into *goal-coordinated* (e.g. keyboard typing, piano-playing or drum-playing, etc.) and *pure bimanual* operations. The non-coordinated operation can be realized by a dual-arm or two single-arm robots using the well-investigated robot motion planning. The goal-oriented operations are the most complicated manual activities done by a human and require a long-term practice. The bimanual operations performed by humans are mostly based on relatively simple motions in both arms, commonly *symmetric* or *asymmetric*, *congruent* or *non-congruent* (Fig. 1). It was recently recognized that the main reason for simplifying arms motion is due to the very complex planning of the dual-arm in real time. Therefore, the human motor cortex generates simple trajectories which are easy to synchronize and monitor during execution.

The main control problems in dual-arm robots are related to the physical contact and interaction between arms (constrained motion) and environment in bimanual contact operations. Impedance control [1, 2] provides a common control approach to cope with uncertainties in robotic arms and environment, as well as to maintain interaction forces within some desired level. Several industrial applications of cooperative and dual-arm robots utilize some variations of master/slave control. In this approach, however, the arms are coordinated rather than cooperatively or interactively controlled. The theoretical background for coordinated *common object motion related control* of multi-arm robots motion was established by Schneider and Cannon [3]. The authors have proposed *object impedance* control approach. This method enforces controlled impedance not of single-arm end-points, but of the common manipulated object itself. In order to maintain arms internal interaction forces which are mutually cancelled and do not influence common object force exerted on environment, Bonitz and Hsia [4] have added the *internal impedance control*. This control is realized in the null-space of the Jacobian mapping the arms end-point forces into the common object frame. Both *external* (describes common object/environment interaction) and *internal* (compensates for errors and internal forces between arms) impedance control approaches (Fig. 2) provide fundamental framework for bimanual interaction control. Various combinations of *external* and *internal compliance control* were tested in experiments with cooperative industrial robots [5] and recently in dual-arm robot system [6] for elemental bimanual operations, such as holding and moving a common object.

Controlling and programming of dual-arm assembly tasks, however, require more complex approaches. The assembly tasks involve various composite motion and transitions phases, e.g. from free-space motion, via unilateral force contact towards completely constrained closed-chain motion of coupled parts. Several researches address the multi-arm motion planning problems focusing common object path planning, motion coordination, collision avoidance etc. Only a few investigations deal with bi-manual compliance control and assembly process planning [7].

This paper addresses the synthesis of the impedance control for the bimanual contact tasks based on robust control design approach developed for single robot-environment interaction. The control issues at bimanual compliance motion control planning and programming

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layers are also considered. These problems were investigated during development of humanoid dual-arm assembly robot "Workerbot" within IP PISA [8] project (Fig. 3). The Workerbot was developed to cope with problems of assembly process capacity flexibility. In the case of increased production volume demands, the robot can be leased by a high-tech company to SMEs and integrated in a working environment sharing the same working space with human workers and performing assembly operations (Fig. 4). Several experiments will illustrate the results of control synthesis and programming.

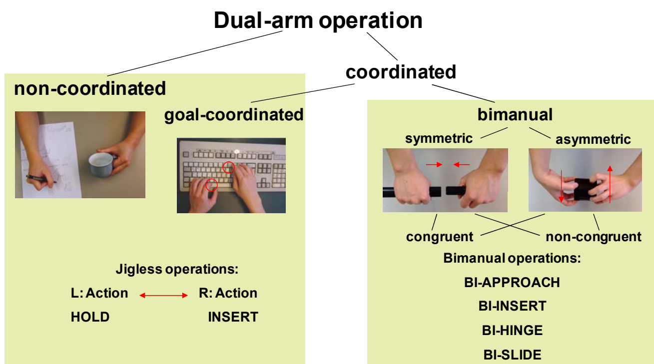

Figure 1. Classification of dual-arm operations

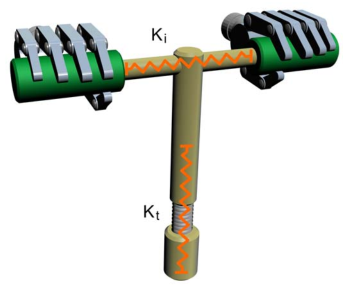

Figure 2. Internal (Ki) and external (target Kt) impedance approaches

II. ROBUST IMPEDANCE CONTROL DESIGN

The impedance control provides a fundamental approach for control of bimanual operations. The control objective of the impedance control is to realize a reference target model specifying the interaction between robot and environment. Commonly the linear second-order differential equation form (1) is adopted, describing the simple and well-understood mass-spring-damper mechanical system

$$F = M_t(\ddot{x} - \ddot{x}_0) + B_t(\dot{x} - \dot{x}_0) + K_t(x - x_0). \quad (1)$$

where x_0 is nominal robot position, $\mathbf{x}$ is the actual one, M_t, B_t and K_t are target mass, damping and stiffness respectively, F is the external force exerted upon the robot. Target impedance $Z_t = G_t(s)$ commonly relates force and velocity. However, in industrial robotic systems it is common to express the impedance in the above form relating forces and position deviations. For a SISO system $G_t(s) = M_t(s^2 + 2\xi_t\omega_t s + \omega_t^2)$, where ξ_t and ω_t denote damping coefficient and target frequency respectively.

Figure 3. PISA time-sharing dual-arm Workerbot

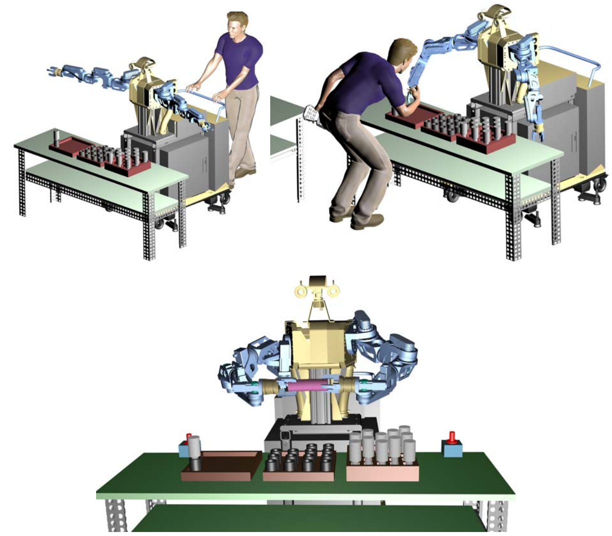

Figure 4. PISA Workerbot operatingscenario: platform moving to a new working place (upper left), commissioning based on manual-guiding and calibration using compliance control (upper right) and finally autonomous bimanual assembly (down).

In order to simplify the synthesis of the impedance controller, the control problem is commonly split into two parts [2]. The first one is realization of the target impedance model (1) in Cartesian-operational space in an arbitrary compliance C-frame attached to the tool-center-point TCP. The second goal is design of the target model to ensure stability of contact transition and coupled system interaction, as well desired performance and robustness.

Target impedance can be realized using various control techniques, e.g. model-based computed torque control [2]. However in conventional industrial robots designed as "positioning devices" it is feasible to implement the position-mode impedance control by closing a force-sensing loop around position controller (Fig. 5). Position- based impedance control does not require any modification of conventional positional controller. Moreover as demonstrated in [2] conventional industrial robot position control systems exhibit several nice features such as diagonal dominancy and spatial roundness in both joint and Cartesian space, which significantly facilitate the realization of the target model. Then the target model (1) can simply be realized using position control error based impedance scheme (Fig 5) closing an external force control loop with the compensator G_f around the internal closed loop position controller G_p (involving axes controllers and robot plant) and applying the following diagonal force compensator

$$G_f(s) = \hat{G}_p(s)^{-1} G_t(s)^{-1} \quad (2)$$

where $\hat{G}_p$ is an estimate of diagonal dominant position control transfer matrix. Detailed position control based scheme including all transformations in different coordinate frames and computation algorithms is presented in [2]. Figure 6 demonstrates the accuracy of the target model realization using controller (2). The measured contact force (realized by manual guiding the robot) and the computed impedance force, calculated based on the model (1) using target parameters in the selected C-frame and measured robot position and motion, match quite good.

The next design step focuses synthesis of the realized target model parameters (1). Some of the target parameters, such as target frequency $\omega_t = \sqrt{k_t / m_t}$, are constrained by the bandwidth of the robot position controller (commonly about 4-6 Hz) in the selected inner/outer loop control structure (Fig. 5). Commonly target systems with bandwidth up to a half of position control bandwidth may be realized (2-3 Hz), which is enough in majority of applications (human arm control bandwidth in manual operations is about 3-5 Hz). The target stiffness is selected to achieve a desired level of compliance (in steady-state), while target damping plays an essential role for stabilization. The goal is to implement a minimum amount of damping ensuring stable interaction in all phases of the contact processes in order to achieve fast system reactions

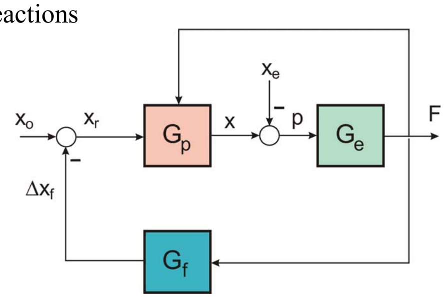

Figure 5. Position-error based impedance control

The robust robot-environment interaction framework [2] considers simplified interaction model of an impedance controlled robot (replaced by target impedance) in contact with a critical most-destabilizing passive stiff environment (Fig 7). After the contact the robot nominal position (x_0) is beyond the initial contact position (x_e). Practically the robot penetrates the environment $p = x - x_e$, (by analogy $p_0 = x_0 - x_e$ will be referred to as nominal-penetration) producing the interaction force. In the impedance controlled robot system this force causes the position deviation (e) from the nominal position (Fig. 5, 7). The robust interaction control frame imposes the following contact transition and coupled stability condition [2].

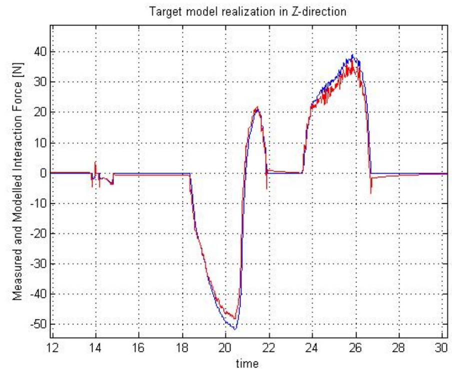

Figure 6. Target model realization (blue-measured force, red-target impedance model force)

Theorem *(Robust contact transition and coupled interaction stability criterion): A sufficient condition for a stable contact transition and interaction of a linearized robotic control system under impedance control from the free space to a unilateral contact with any passive environment, is that the 2-norm/2-norm system gain of the feedback system with the input-output pair* $\{p_0, e\}$*, i.e. the* $\infty -$ *norm of the corresponding transfer function matrix* $\left[I + G_e^{-1}(s) G_t(s)\right]^{-1}$*, be less than 1.*

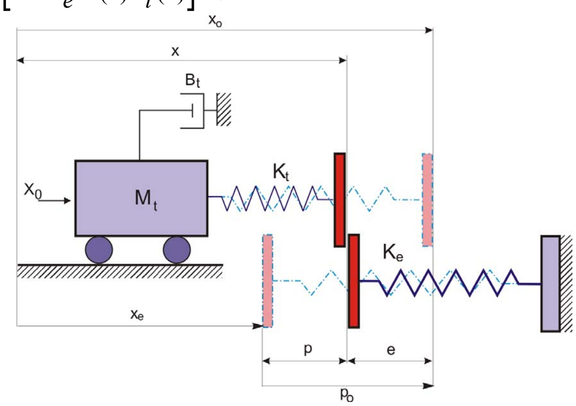

Figure 7. Impedance controlled robot-environment interaction model

As demonstrated in [2] the robust control design framework provides several crucial advantages for the practical control synthesis. The main benefits are simplified interaction model, as well as possibility to consider specific systems non-linearities and uncertainties by means of structural perturbations. Furthermore it provides a synthesis oriented approach in both s- or z-domains using nice features Tustin-transform which preserves H_∞ norm. Essential destabilizing time delays (e.g. due to force measurements and processing, as well as control computations) in real sampled data (SD) control systems are also considered in design. Moreover, based on the bilinear sector (Cayley's) transform equivalence between robust control based and passivity based stability, which is a basic approach for the interaction control, has been established in [2]. Different from the Colgate and Hogan absolute robot passivity based approach [9], the robust design approach (3) introduces the environment in the synthesis which is considerably less conservative approach. This results in a significant reduction of the high apparent robot inertia (up to 95%) and stiffness which is essential for dual-arm interaction with environment. An accurate knowledge of the environmental stiffness, which can also vary during control of a contact interaction task, represents critical issue in industrial robot practice. As demonstrated in [2], the robust control design permits the error of stiffness estimates or task variations up to 100% without jeopardizing contact transition and coupled stability, which is the crucial practical benefit for the interaction control synthesis.

For an idealized sampled-data model, assuming time delay to be a whole-numbered multiple of sampling time $\tau = nT$, the synthesis may be performed based on discrete form of the robust stability criterion

$$\left\| \left[I + z^{n} G_{e}(z)^{-1} \hat{G}_{t}(z) \right]^{-1} \right\|_{\infty} < 1 \qquad (3)$$

The numerical control synthesis procedure [2] assumes an environmental stiffness, as well as target frequency and stiffness, and increases the target damping until above condition is fulfilled.

The above design procedure can be extended for dual-arms considering realized target systems interaction (Fig. 8). Instead of the environmental stiffness the target stiffness of the interacting arm should be taken in the design. Since the target stiffness is considerably less than the environmental one, it is obvious that the stabilization of dual-arms interaction is significantly simpler than contact between an arm and stiff environment. Consequently the reachable performance (e.g. reduced force-overshoots due to smaller required damping, faster reaction and task completion etc.) in dual-arm interaction is considerably higher in comparison to the single robot. In conjunction to the kinematic advantages (e.g. redundancy, manipulability etc.) and jigless operation, easier contact stabilization and reduced interaction forces provide additional advantages of dual-arm assembly over the single-arm robot operation.

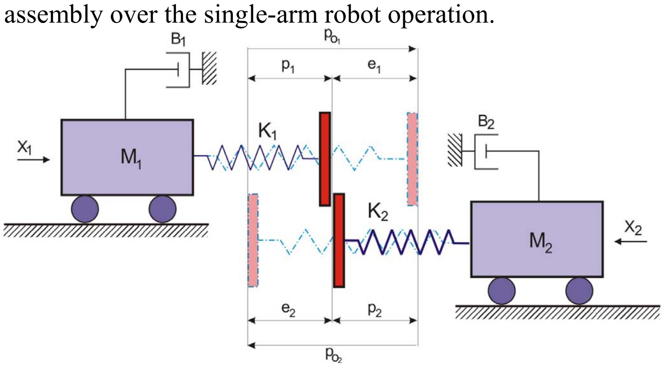

Figure 8. Two target models representiang bimanual interaction

III. Planning of Bimanual Contact Task

A common dual-arm robot world model with absolute and relative coordinate frames associated with objects and features of interest is shown in (Fig. 9). Beside coordinate frames which are convenient for the programming of robot motion in the free space (e.g. robot base B-, end-point E-, tool T-frame etc.), impedance control system includes two new frames specific for the compliant motion programming: force sensing S and compliance frame C. The S-frame is a force-sensor specific frame in which the forces and torques are measured. This frame is defined relative to the robot end-point E. With respect to the C-frame the target impedance behaviour (robot impedance reaction) is specified and controlled. Since the location of the C-frame depends on the current task, we have chosen as most convenient to specify the C-frame relative to task T-frame (Fig. 10) taking into account that T-frame also is a variable frame selected to meet specific task motion requirement.

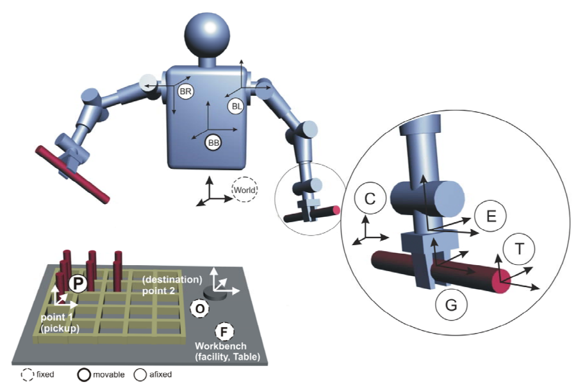

Figure 9. Dual-arm world model

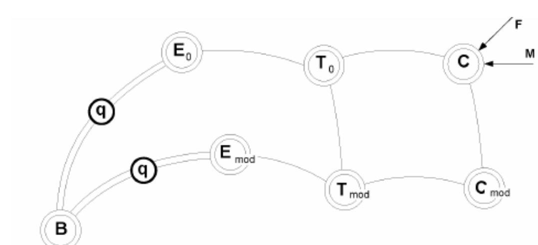

Figure 10. Compliance frame

The nominal motion correction is computed based on (Fig. 10)

$${}^{0}T_{r} = {}^{O}T_{T}\,{}^{T}T_{C}\,\Delta T^{C}_{imp}\,{}^{T}T_{C}^{-1} \qquad (4)$$

where ${}^{O}T_{T}$ is the homogenous matrix describing the actual desired T-frame position in an object frame, ${}^{0}T_{r}$ is corrected reference position, ΔT^{C}_{imp} is incremental position modification (in C frame), ${}^{T}T_{C}$ defines the location of C-frame w.r.t. T-frame. A customary object-oriented programming approach simplifies dual-arm robot compliance motion programming by formulating bimanual actions in a natural way, in terms of operations on the common object being manipulated. The essential bimanual actions (Fig. 11) involve non-contact (e.g. BI-Approach-

Retract, BI-Move, etc.) and contact (e.g. BI-Grasp-Release, BI-Insert-Extract, BI-Slide, BI-Hinge, BI-Hold, BI-Yield, etc.) actions.

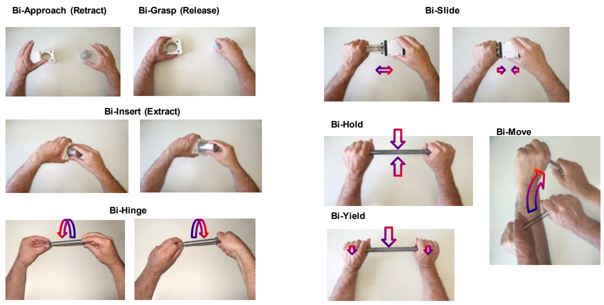

Figure 11. Bi-manual elemental actions

A combination of synchronized single arms and bimanual actions realizes a complex assembly task (e.g. INSTALL, ASSEMBLY etc.). An example in (Fig. 12) provides decomposition of ASSEMBLY-BY_SCREWING task into single-arm and bimanual elemental actions.

R-Arm	Dual-Arm	L-Arm
MOVE_ALONG (traj_f1_R) APPROACH (f1, s1) ATTACH (f1, s1) RETRACT (f1, s1) MOVE_ALONG (traj_f3_R)		MOVE_ALONG (traj_f2_L) APPROACH (f2, s2) ATTACH (f2, s2) RETRACT (f2, s2) MOVE_ALONG (traj_f3_L)
	BI_APPROACH (s1, s2) BI_GET_CONTACT (s1, s2) BI_HINGE_ASYM (s1, s2)	
DETACH (s1) RETRACT (s1)		HOLD
MOVE_ALONG (stdby_R)		MOVE_ALONG (f3, s3) APPROACH (f3, s3) INSERT_PORT (f3, s3) DETACH (f3, s3) RETRACT (f3, s3) MOVE_ALONG (stdby_L)

Figure 12. Decomposition of ASSEMBLY_BY_SCREWING task into single-arm and bimanual actions. In this task the right and left arm takes the parts (subject s1 and s2) from containers (facilities f1 and f2) and perform screwing by means of BI-Hinge (asymmetric) action

IV. HIGH-LAYER CONTROL ALGORITHMS

The basic specification of the compliance control algorithms in general involves: location of C-frame and tool-frame, selection of target-impedances i.e. control gains (realizing target model and ensuring stable contact transition and interaction) for performing the task, and a set of robot motion commands to be performed by arms. The bimanual operations thereby offer novel possibilities to realize contact operation in an easier and faster way. The following insertion examples illustrate planning of practical bimanual contact task using impedance control functions and commands.

For sake of simplicity we will consider peg-hole insertion. Impedance based bimanual insertion is mainly based on the single arm-insertion algorithm [2]. This algorithm provides a similar approach as RCC passive assembly devices. The control system capabilities to change impedance control gains (i.e target models) and compliance frames in various insertion phases provide effects as a "free programmable RCC device". The bimanual insertion algorithm is like in single arm commonly split into three phases: engagement, insertion and termination (Fig. 13). The selection of impedance gains (realized in the program language using descriptive linguistic variables, such as HIGH-, MEDIUM- and SMAL-IMPEDANCE, i.e. DAMPING for the damping control.) in these phases is presented in (Fig. 14).

Engagement is faced with parts chamfers meeting and sliding past one another. The following impedance control specification is introduced for the engagement phase:

- C- frame should be located near to interacting forces directions (on peg and hole top, see Fig 13);
- The insertion (i.e. engagement) motion consists of linear relative peg/hole displacements along the nominal hole/peg axis. The goal pose is chosen bellow the nominal front surfaces (even below chamfers).

A medium stiffness (Fig. 14) in the axis z-direction during engagement is selected taking into account that the robot motion is in fact unconstrained in this direction. To slide along chamfers, the stiffness in lateral directions (x, y) must be less than the axial one causing faster misalignment than the surface encountering (the lateral forces/stiffness behavior serves as a cue to the desired corrective motion). This also reduces contact forces allowing the peg/hole to cope easily with the friction. High rotational stiffness for both peg and hole is required taking into account the engagement goal to compensate for lateral misalignment only without introducing unwanted rotations. In some specific cases (e.g. parts with relatively small chamfers), however, it is useful to command initial angular misalignment of peg or hole (Fig. 15) in order to the chamfers and facilitate insertion.

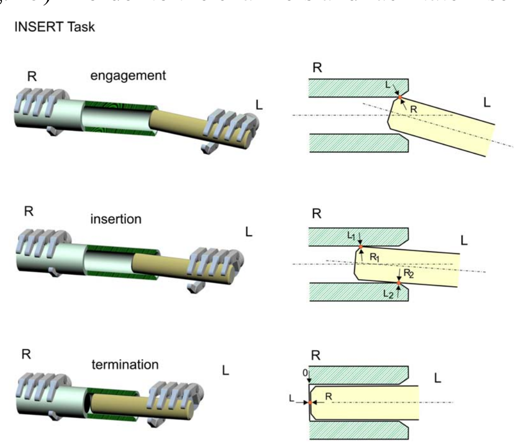

Figure 13. Bimanual insertion action phases

Under some circumstances, even the engagement without chamfers can be realized in dual-arms by proper selection of compliance frames (Fig. 16) and gains. In this case rotational alignment of both arms (i.e. peg and hole) is useful to meet the opening gap. In general case, however, the assembly of parts without chamfers requires specific algorithms (e.g. "blind like opening search") which assume a larger hole front surface. For a simple compliance based insertion the chamfers on both peg/hole are essential.

At the end of the engagement (after a specified engagement depth is achieved), the *insertion* strategy is started. At first the contact forces are relaxed using the relax algorithm. Thereby the location of the C-frame remains close to the peg top. The insertion phase is characterized by the following settings (Fig. 14):

- The C frame remains located near the peg top;
- The lateral rotation impedances (stiffness) around the *x* and y C-frame directions are switched to LOW in order to compensate for rotational errors. The impedance in the insertion direction (*z*) along the hole is set to MEDIUM since the robot motion is unconstrained in this direction and has to compensate for disturbing friction forces between the peg and the hole during insertion. In specific cases LOW impedance in lateral directions can also be applied;
- The insertion motion consists of relative linear displacements in the positive *z*-direction along the peg/hole axis.

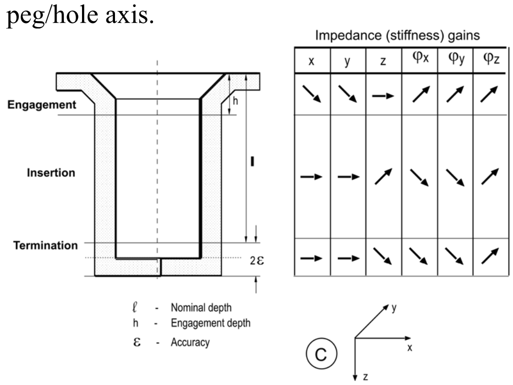

Figure 14. Impedance level selection in insertion phases

The insertion phase is terminated when a termination pose in front of the peg bottom is reached. The residual forces occur at the end of both phases due to misalignment between the peg insertion direction and the hole axis, which is corrected using the impedance spring-effects. In order to pursue with the termination phase and to change impedance gains according to the termination strategy, these residual forces must be relaxed.

A special *relax* algorithm has been implemented to obtain bumpless parameter variations (gains and C-frame locations). The relax algorithm switches compliance control from running to the monitoring state and reset position correction offset. Then the damping control gains are selected in all directions and impedance control is activated (running mode). Due to contact forces the arms move until given small force threshold is reached in all directions during selected time period. Finally the impedance control is again switched to the monitoring and offset reset. By this means the contact is maintained and forces/torque reduced to the level which allows smooth compliance control parameter variations.

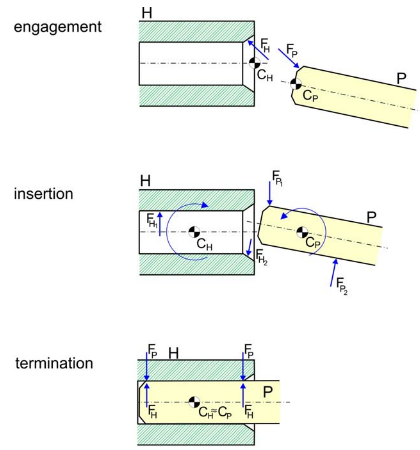

Figure 15. C-frame locations

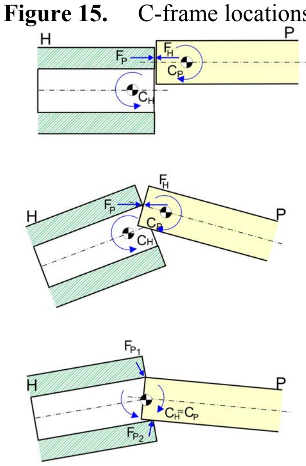

Figure 16. Specific case engagement without chamfers

Specific for the insertion relaxing is that the location of the C-frame should be changed near the middle point of hole in order to achieve a consistent condition for the relaxing of both the residual force and moment components. Figures (17) illustrate dual-arm insertion experiment according to the described algorithms with Workerbot system. It is worth mentioning that the interaction force level in dual-arm assembly is considerable lower in comparison to the single arm assembly [2] due to compliant behavior of both peg and hole, smaller system stiffness and better control performance.

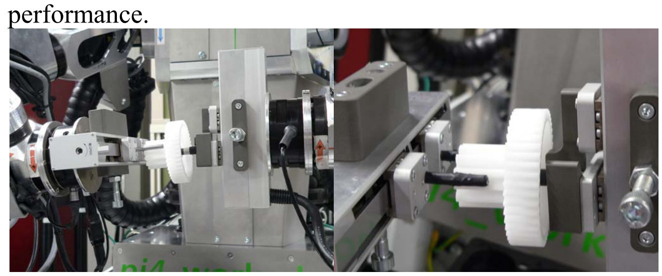

Figure 17. Insertion experiment with the Workerbot

V. Dual-Arm Robot Programming Language

The Dual-Arm Robotic language DA-RL is a C++ based robotic language developed to support programming of Workerbot dual-arm robotic applications within developed control system (implemented in RT-Linux environment using OSADL preemption-patch RT solution). This language is realized in a standard C++ environment and utilizes the C++ language components: syntax, data representation, program structures, basic functions and libraries. In the following only a short presentation of the specific DA-RL features related to the dual-arm programming will be given.

The DA-RL encompasses all relevant robot objects, such as POSE, FRAME (according to the adopted world model), VELOCITY etc. and methods for setting/getting the robotic arm parameters. The specific *arm objects* relate to the *left*, *right* or *both arms* supporting bimanual programming. The command object group includes elemental motion commands, such as MOVE_LIN, MOVE_CIRC, MOVE_PTP etc. Specific commands control external devices (e.g. grippers).

A robot movement commands consists of several motion commands objects assigned to a specific arm object, such as:

```
rArm<<pegL[0].getCartPose(S_APPROACH_ATTACH;
rArm.executeBlocking();
```

which assigns a goal pose of the pegL (relative approach_for_attach position on the subject) to the right arm. The *blocking/non-blocking* identifiers are used in order to prevent/allow the execution of the next block before the actual assignment block has not been completed. The *smooth* identifier defines continuous motion (transition) between path segments (e.g. LIN, CIRC).

A specific set of commands support impedance control, such as:

```
lArm.setIMCOStatusBlocking(SYSTEM_STATUS_MONITORING);
lArm.setComplianceGains( gLowStiff );
lArm.setComplianceFrame( CartPose() );
lArm.setIMCOStatusBlocking(SYSTEM_STATUS_RUNNING);
```

Synchronized bimanual movements are controlled via bi-objects, such as:

```
biMovePTP(lOverFacility, rOverFacility);
biExecuteBlocking();
```

Synchronization in complex arm operations may be controlled using synchronization flags (A, B; C) e.g.:

```
lArm <<
pegL[3].getCartPose(S_APPROACH_ATTACH) <<
pegL[3].getCartPose(S_GRASP_POSE) << A      << B <
pegL[3].getCartPose(S_APPROACH_ATTACH) //
lGripper << Open()       << A << Close() << B;
rArm <<
holeL[0].getCartPose(S_APPROACH_ATTACH) <<
holeL[0].getCartPose(S_GRASP_POSE) << A          << B
<< cogL[0].getCartPose(S_APPROACH_ATTACH);
rGripper << Open()
```

The C++ DA-RL implementation allow efficient usage of rich available library and programming and communication tools, as well as implementation of complex actions and task commnads by expert programmers, and easy utilization and combination of high-layer commands by non-expert users.

VI. CONCLUSION

The experimental testing and experience with the new Workerbot dual-arm control system have proven the reliability of the presented algorithms for compliant motion control. Certainly, the basic precondition for implementing compliant motion control is the design of robust servo impedance controller ensuring stable transition and coupling with the environment. A proper selection of the C-frame location and target impedance gains are crucial for a successful execution of the impedance control tasks. This selection should be compatible with the very nature of the dual-arm motion constraints, i.e. contact task geometry and physical task (force/motion relationships). The compliance control dual-arm bimanual operation exhibit considerably better performance in comparison with single-arm assembly of stiff parts. The control integration and programming issues, often underestimated in the literature, are essential for a customary and efficient application of impedance control in practical dual-arm contact tasks. The novel DA-RL programming language developed in a standard C++ environment provides efficient and flexible programming tool to cope with complex dual-arm assembly operations.

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