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# Performing Assembly Task Under Constraints Using 3D Sensor-Based Control

Sylvain Vandernotte<sup>1</sup>, Abdelhamid Chriette<sup>2</sup>, Adolfo Suarez Roos<sup>3</sup>, and  
Philippe Martinet<sup>2</sup>

<sup>1</sup> IRT Jules Verne, Chemin du Chaffaut, F-44340 Bougenais, France

<sup>2</sup> IRCCyN, UMR CNRS 6597, 1 Rue de la Noe, F-44321 Nantes Cedex, France

<sup>3</sup> Airbus Group Innovations, 13 Rue Pasteur, F-92152 Suresnes, France

**Abstract.** Basic robotic operations such as grasps of structure’s parts and their placement are mostly model-based and do not take into account modelling error and geometry variations. As consequences, quality of the assembly cannot be trusted. In this paper, we propose to use 3D sensor and sensor-based control to improve the precision a positioning task. The interaction matrix is constructed upon assembly constraint definition. Those assembly constraints are taken into a task sequencing mechanism, with others robot-specific and environment tasks. The positioning operation is tested with Gazebo simulator and ROS environment and demonstrate the effectiveness of the approach.

## 1 Introduction

Assembly tasks become an active field of research in robotics community. Industrial companies already benefits of robots for highly repetitive and low accuracy tasks such as welding or palletization tasks, in order to improve their productivity and reduce their functional costs. However, others are still difficult to automate. Non-controlled environment, low mobility and low perception capacities are the main obstacles for this. Car, planes and boats are all manufactured products that require significant effort for their assembly. There are still a non-negligible amount of tasks in the production process where parts, structures and others components are installed by hand. This kind of operation would require a certain degree of dexterity and mobility of the hand, the wrist and the arm, but not only. An assembly task hides a lot of small intermediate steps in order to place the objects successfully. It goes from identifying its final location in a complex environment, to handle motion toward this pose without undesired contacts, passing through gathering the necessary documentation.

Previous works in assembly using robots mainly focused on planning robot’s motion and managing resources. In [12], the authors built a top-level construction algorithm to manage a team of mobile robots to construct truss structures. Robots are specialized in two functions: assembling and delivering. The algorithm coordinates the assembly to maximizing parallelism across assembly robots and conforming to physical constraints of the structure. In a same way, [9] designed an algorithm that produces a sequence of assembly tasks while they take into account timing constraints and parts availability. [15] designed a planner

that generates an assembly sequence to construct a three-dimensional product from modular units. In [14] and [13], assembly tasks is defined based on predefined function blocks that describe elementary assembly function, in order to transform a previously generated assembly sequence into predefined robot’s motion. These efforts are necessary but do not met industrial needs at this time. Most of industrial companies use large-scale CAD softwares which help them to manage resources and schedule the assembly.

Industrial needs are more about how to use robots in complex and non-controlled environment. All these previous approaches require a perfect knowledge of the environment to ensure the success of the assembly. Robot’s motion with respect to objects (structures, parts) are model-based, which means that they do not take into account part geometry and position variations. Visual servoing [5] and 3D sensor-based control techniques already prove their ability to perform robust control based on real world measured features. These techniques and new types of 3D sensors are mixed in a new way to perform assembly tasks by a manipulator robot. 2D features in visual servoing control have several drawbacks, such as not straight end-effector cartesian trajectory or local minima, which disqualify them for assembly tasks. In contrary, 2D features associated with depth information [2] showed similar performances to 3D features. Equivalently, [3] and [4] proposed to improve image-based visual servoing using 3D features in order to get straighter cartesian trajectory and enhanced convergence region. Finally, [10] prove that control based on 2D points features and depth is globally stable with any initial conditions.

All previous works related to assembly operations performed by robots assume that the world exactly corresponds to its model. Robotic operations are done considering neither localization errors nor geometry variability of the part. Thanks to sensor-based control schemes, the idea is to significantly improve the absolute precision of the end effector pose with respect to local reference features where the robot task definition relies on the assembly semantics. The main contribution of this paper is to define a task-formalism control framework that can mix assembly constraints (coincident plane, point-to-plane distances, etc.) and robot-specific constraints (joint limit, singularities, collisions, etc.). It focuses on the interaction matrix definition based on assembly constraints and its integration in a task sequencing scheme. A precise approach of the final pose of the part is considered and simulated. The case is fixing a shelf on a wall, the simulation shows the robot bring the fixture very close to its final pose.

The paper is organized as follows: section 2 describes the scene, the task definition and its corresponding interaction matrix for one assembly constraint. The multi-tasks hierarchical control scheme is explained in section 3. Finally, simulation results are shown in section 4.

## 2 Relative positioning using assembly constraints

We want to demonstrate that the robot arm is able to perform a precise positioning task using sensor-based control techniques and assembly constraints.

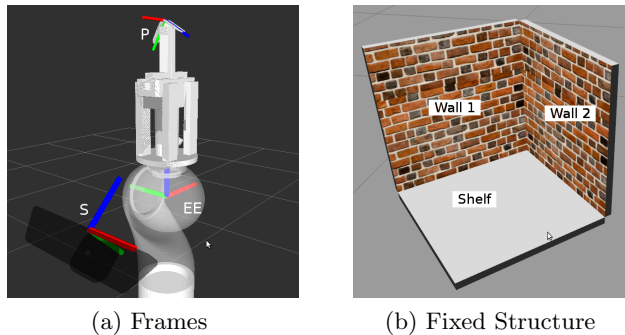


Fig. 1: Frames disposition at end effector of the KUKA LWR4+. Frames  $EE$ ,  $S$  and  $P$  represent respectively the end effector frame, the sensor frame and the part frame.

The experiment will lead to a positioning task of a part with respect to a structure where the part is supposed to be assembled. It can be seen as an operation of placing a fixture to mount a simple shelf on a wall, considering that fixation can be completed by another robot or an operator. Only the positioning before establishment of the contact is considered in this paper. The part is placed at predefined distance of the structure by using three plane-to-plane distance constraints.

The scene is composed of the robot next to the structure. The robot arm used in simulation is the KUKA LWR4+ with seven degrees of freedom (DOFs). The shelf is placed in a corner of a room at a certain height, so that the structure can be seen as a collection of three rigid orthogonal planes. The part is held thanks to a parallel-jaw gripper attached on the robot's end effector. It is assumed that the pose of the part with respect to the end effector frame is known and rigid (the part can be considered light enough to avoid slippage when held). The final pose of the part is also reachable by the robot. Distances are measured from part to plane by a depth sensor attached to the end effector link. Finally, we assume that the simulated environment is simple enough to avoid occlusion of measured features from the sensor. See figure 1 for illustrations.

Assembly constraints describe how parts – or a set of parts – are arranged to be fixed onto another one. Without a loss of generality, a constraint can be defined as a collection of two features of each sets (faces, edges, points, planes, etc.) and a local geometric description of their position between each other. Coincident planes, for example, is a constraint that makes two planes of each set parallel with a distance along their normals equal to zero. It can be named also plane-to-plane distance. This type of constraints fix only 3 DOFs in space (1 translation and 2 orientations). We need three such constraints with orthogonal direction to set the whole pose of the part, as shown in figure 2a. Coincident 3D points in space fix the three translations but do not constraint orientation. The positioning task is done by using three plane-to-plane distance constraints to place our part really close to the structure before making contact. The distance

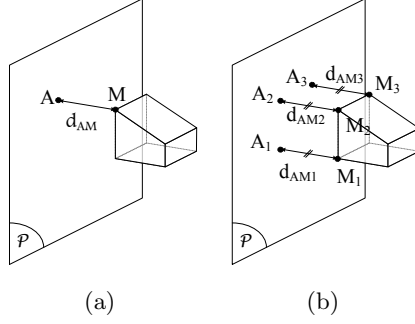


Fig. 2: Illustration of plane-to-plane distance constraints.

is estimated from sensor stream. The sensor gives a point cloud as output, the cluster of points corresponding to the structure is extracted. Plane equations is then deduced. Related work can be found in [7] where they use of structured light and a camera to constraint the robot's end effector with respect to a plane. Here, 3D informations brings the possibility to simplify the task definition.

From the plane equation, the estimate of the distance between plane  $\mathcal{P} = [a \ b \ c \ d]^\top$  and an arbitrary 3D point  $M = [x_M \ y_M \ z_M]^\top$  is,

$$d_{AM} = \frac{ax_M + by_M + cz_M + d}{\sqrt{a^2 + b^2 + c^2}} \quad (1)$$

where  $A$  is the orthogonal projection of  $M$  on  $\mathcal{P}$ . From this, the plane-to-plane distance constraint can be reformulated equivalently as three point-to-plane distances, under conditions that all three points belong to the same plane, they are not aligned and all distances are equal.

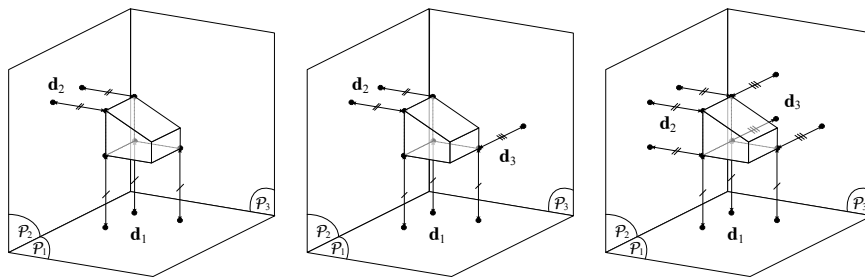
In order to build the interaction matrix of the point-to-plane constraint, two 3D points  $L = [x_L \ y_L \ z_L]^\top$  and  $M = [x_M \ y_M \ z_M]^\top$  are considered such as  $LM$  is collinear with  $\mathbf{n}$ . The distance  $d_{LM}$  is given as the sum of the distance from  $L$  to  $\mathcal{P}$ , and from  $M$  to  $\mathcal{P}$ :

$$d_{LM} = \frac{ax_L + by_L + cz_L + d}{\sqrt{a^2 + b^2 + c^2}} + \frac{ax_M + by_M + cz_M + d}{\sqrt{a^2 + b^2 + c^2}} \quad (2)$$

One can deduce the interaction matrix that maps the evolution of the distance  $\dot{d}_{LM}$  to the evolution of the both 3D points:

$$\mathbf{L}_d = \frac{\partial d_{LM}}{\partial L} = \frac{\partial d_{LM}}{\partial M} = \frac{1}{\sqrt{a^2 + b^2 + c^2}} [a \ b \ c] \quad (3)$$

This interaction matrix holds for any couple of points that form a vector collinear with the plane normal.  $L$  is then replaced by  $A$ . Since  $A$  belongs to the plane, equations (2) and (1) are equal, but the interaction matrix  $\mathbf{L}_d$  still holds. The interaction matrix can be completed to express  $\dot{d}_{LM}$  in function of the sensor velocity tensor  $\mathbf{v}$  such as:



(a) 5 distances: 5 DOFs con- (b) 6 distances: 6 DOFs con- (c) 9 distances: 6 DOFs con-  
 strained strained strained, redundant

Fig. 3: Use of distances to place the part. (a) shows a positioning task with respect to two planes, (b) and (c) with respect to three planes. Since 5 DOFs are constrained by  $\mathcal{P}_1$  and  $\mathcal{P}_2$ , there only need to consider only one distance to complete the third sub-task.

$$\dot{d}_{AM} = \mathbf{L}_d \mathbf{L}_A \mathbf{v} \quad (4)$$

where  $\mathbf{L}_A = [-\mathbf{I}_3 [A]_{\times}]^1$  is the interaction matrix of the 3D point  $A$ .

Using this, the interaction matrix for a plane-to-plane constraint is the stack of three interaction matrices defined in equation (4).

$$\dot{\mathbf{d}} = \begin{bmatrix} \dot{d}_{A_1 M_1} \\ \dot{d}_{A_2 M_2} \\ \dot{d}_{A_3 M_3} \end{bmatrix} = \begin{bmatrix} \mathbf{L}_d \mathbf{L}_{A_1} \\ \mathbf{L}_d \mathbf{L}_{A_2} \\ \mathbf{L}_d \mathbf{L}_{A_3} \end{bmatrix} \mathbf{v} \quad (5)$$

Hereafter is given the complete  $3 \times 6$  interaction matrix  $\mathbf{L}$  for one plane-to-plane constraint:

$$\mathbf{L} = \frac{1}{\sqrt{a^2 + b^2 + c^2}} \begin{bmatrix} -a & -b & -c & bz_{A1} - cy_{A1} & cx_{A1} - az_{A1} & ay_{A1} - bx_{A1} \\ -a & -b & -c & bz_{A2} - cy_{A2} & cx_{A2} - az_{A2} & ay_{A2} - bx_{A2} \\ -a & -b & -c & bz_{A3} - cy_{A3} & cx_{A3} - az_{A3} & ay_{A3} - bx_{A3} \end{bmatrix} \quad (6)$$

Special attention is needed about the task's objective: it is defined along the normal direction of the plane, depending on how the plane is extracted from sensor data. If the direction in the task definition is the opposite of the extracted plane, the control law could diverge and the system behaviour would not be as expected. The next section shows how the constraints are put together.

### 3 Constraints-based control

#### 3.1 Ensuring assembly constraints using sub-tasks

In a assembly operation, satisfying all constraints at same time could be difficult. Some of them could exert contradictory command on the same DOF. Or one have to be set before others to perform the assembly, which can be seen as an higher

<sup>1</sup>  $[A]_{\times}$  denotes the  $3 \times 3$  skew symmetric matrix of  $A$ .

priority upon the other constraints. At a human level, perform an assembly task looks more like following assembly constraint under a priority scheme decided after examining the two parts, rather than forcing the assembly under the risk of damaging it. Here, we want to follow the same kind of idea for our positioning task. As previously said, the task rely on three plane-to-plane constraints with orthogonal direction, so that the part's pose is fully constrained. But on the other hand, one of these would fix 3 DOFs, making the task redundant. Conflicts are avoided by using only the necessary number of distances for each constraints, as shown in figure 3b. Moreover, a task sequencing scheme is used to apply each constraint following a priority order to the robot control.

Let us say that the three constraints have to be set following an arbitrary priority order, such that placing the part with respect to the shelf (plane  $\mathcal{P}_1$ ), is more important than the first wall ( $\mathcal{P}_2$ ) and placing with respect to the first wall is more important than the second ( $\mathcal{P}_3$ ). By doing this, three sub-tasks are defined, so that they can be taken into account using the redundancy formalism.

### 3.2 Considering one constraint

Let  $\mathbf{q}$  be the vector of joint position of the robot, and  $\mathbf{e}_i$  the task function associated to one constraint. The joint velocities  $\dot{\mathbf{q}}$  are inputs for the robot control. The complete interaction matrix for one constraint is:

$$\dot{\mathbf{e}}_i = \mathbf{L}_{\mathbf{d}_i} {}^s\mathbb{T}_e {}^e\mathbf{J}_e \dot{\mathbf{q}} \quad (7)$$

where,  $\mathbf{L}_{\mathbf{d}_i}$  is the interaction matrix defined at equation (5),  ${}^s\mathbb{T}_e$  the velocity twist transformation matrix from the sensor frame to the end effector frame and  ${}^e\mathbf{J}_e$  kinematic matrix of the robot. For the rest of the paper, the task jacobian  $\mathbf{J}$  is defined as the following:

$$\mathbf{J}_i = \mathbf{L}_{\mathbf{d}_i} {}^s\mathbb{T}_e {}^e\mathbf{J}_e \quad (8)$$

The controller aims to regulate the error  $\mathbf{e}_i$  to zero according to a reference behaviour  $\dot{\mathbf{e}}_i^*$  defined such that:

$$\dot{\mathbf{e}}_i^* = -\lambda(\mathbf{d}_i - \mathbf{d}_i^*) \quad (9)$$

where  $\mathbf{d}_i$  and  $\mathbf{d}_i^*$  respectively stand for the measured distance and its objective.

The joint velocities deduced from  $\dot{\mathbf{e}}_i^*$  is given by the least square inverse of (7):

$$\dot{\mathbf{q}} = \mathbf{J}_i^+ \dot{\mathbf{e}}_i^* \quad (10)$$

where  $\mathbf{J}_i^+$  represent the Moore-Penrose pseudoinverse of  $\mathbf{J}_i$ .

So far, the control law is not stable since the robot is not fully constrained. It is explained by the rank of  $\mathbf{J}_i$  ( $m = 3$ ) smaller than the number of DOF of the robot ( $n = 6$ ). The control law is continuous as long as the direction of the desired distance is not parallel the plane normal.

### 3.3 Taking into account all the constraints

As already said, the three constraints are considered following a priority order defined in section 3.1. Since the task jacobian is rank-deficient with respect to the number of DOF of the robot, a second criterion can be used in equation (10) using the redundancy formalism [8]:

$$\dot{\mathbf{q}} = \mathbf{J}^+ \dot{\mathbf{e}}^* + \mathbf{P} \mathbf{z}_{\dot{\mathbf{q}}_2} \quad (11)$$

where  $\mathbf{P}$  is the projection operator onto the null space of the task jacobian  $\mathbf{J}$  and  $\mathbf{z}_{\dot{\mathbf{q}}_2}$  an arbitrary vector which can be used to apply a second control referring to an other sub-task. Thank to (11), motion defined in the secondary task could be performed without disturbing the first task, having a strict higher priority.

Let be  $\mathbf{e}_1$ ,  $\mathbf{e}_2$ ,  $\mathbf{e}_3$  task functions associated respectively to the constraints associated to the shelf, to the first wall and to the second wall, the equation (11) is generalized by using the efficient task sequencing scheme [11], ensuring the proper hierarchy between between all sub-tasks. For the first sub-task  $\mathbf{e}_1$ , motion is deduced such as in (10).

$$\begin{aligned} \dot{\mathbf{q}}_1 &= \mathbf{J}_1^+ \dot{\mathbf{e}}_1^* \\ \mathbf{P}_1 &= \mathbf{I}_n - \mathbf{J}_1^+ \mathbf{J}_1 \end{aligned} \quad (12)$$

The following recursion is used for the two others:

$$\begin{aligned} \dot{\mathbf{q}}_i &= \mathbf{J}_i^+ \dot{\mathbf{e}}_i^* - (\mathbf{J}_i \mathbf{P}_{i-1}) (\dot{\mathbf{e}}_i^* - \mathbf{J}_i \dot{\mathbf{q}}_{i-1}) \\ \mathbf{P}_i &= \mathbf{P}_{i-1} - (\mathbf{J}_i \mathbf{P}_{i-1})^+ (\mathbf{J}_i \mathbf{P}_{i-1}) \end{aligned} \quad (13)$$

for  $i = 2, 3$ . The joint velocities realizing all tasks is  $\mathbf{q}_3$ . Similarly as equation (11), the product  $\mathbf{J}_i \mathbf{P}_{i-1}$  is orthogonal to the task jacobian  $\mathbf{J}_j$  of sub-task  $\mathbf{e}_j$  having higher priority over  $\mathbf{e}_i$ , meaning that all sub-tasks are fully decoupled from each others. In our case, considering all nine distances (figure 3c) together would yield to a redundant system. Here, by using the equation (13), unnecessary components of the second and third redundant sub-tasks would be removed by the action of the orthogonal projector.

## 4 Simulation Results

The aim of this paper is the precise positioning task before establishing the contact to complete the assembly. All simulations were made using Gazebo Simulator [6] and ROS environment [1]. The context of the experiment is the following: the robot grasps a part in a way that makes possible the assembly task without undesired collision between the robot and its environment. The pose of the structure is approximately known and the final pose of the part is defined with respect the structure frame. So that the part could not be placed precisely up the knowledge we have of the scene. However, the robot brings the part the closest to the desired pose as best as it can. Next, it will use the sensor-based control scheme presented in previous sections to ensure a precise pre-positioning operation before making contact, relying on the plane-to-plane distance constraints.



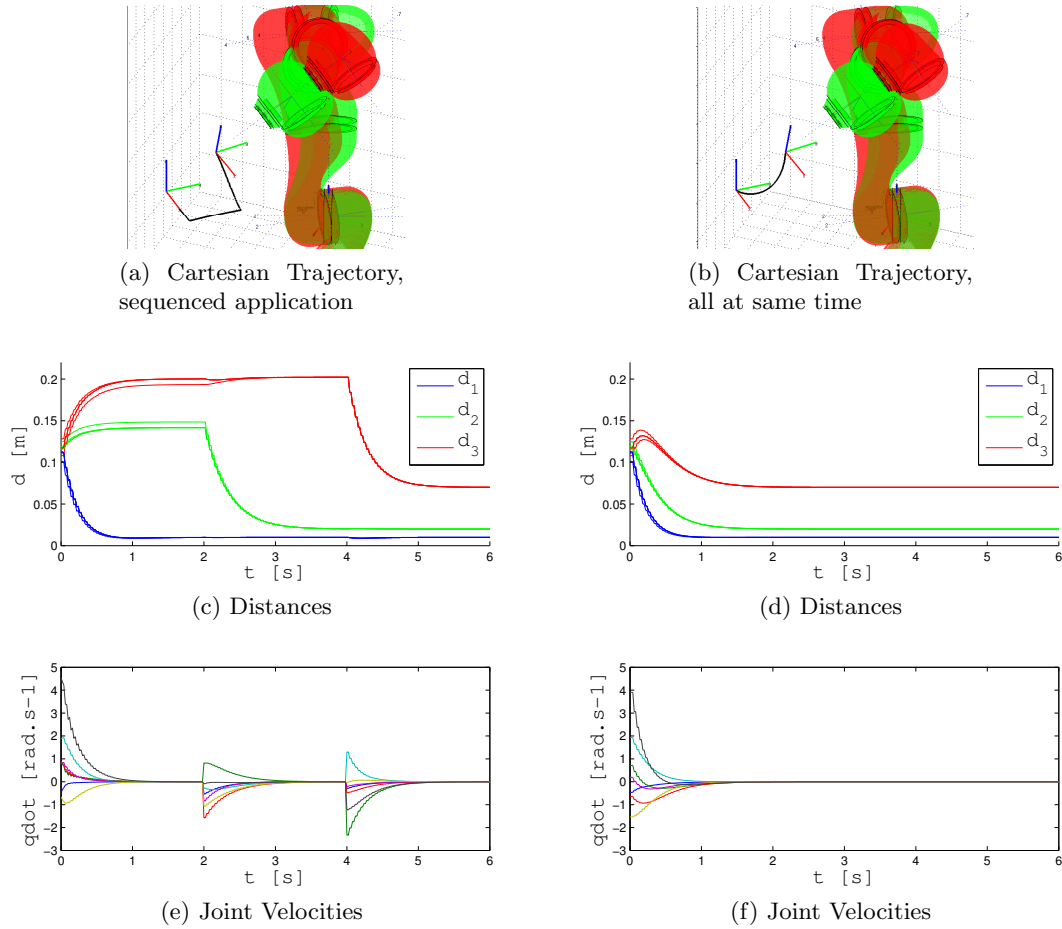


Fig. 4: Precise positioning with plane-to-plane constraints.

Two experiments were conducted to check convergence of the control law.

First experiment is constructed to approach the worst case where the pose of the structure is badly calibrated, so that the translational error between reached uncertain desired pose and the real one is up to  $10\text{cm}$  and its rotational error up to  $\pm 10^\circ$ . Distance objectives for each sub-task are respectively, in priority order,  $1\text{cm}$  far from the shelf,  $2\text{cm}$  from the first wall and  $7\text{cm}$  from the second.

Figure 4a, 4c and 4e are obtained applying sub-tasks at different time step, respectively  $0\text{s}$ ,  $2\text{s}$  and  $4\text{s}$ . Sub-tasks  $\mathbf{e}_2$  and  $\mathbf{e}_3$  are activated by releasing the distance error in program. All distances reaches their objective at the end of operation, which means that the control law converges. As seen in figure 4c, the application of  $\mathbf{e}_2$  has no effect on  $\mathbf{e}_1$  and the application of  $\mathbf{e}_3$  has no effect on the two others. The figure 4b shows us that the cartesian trajectory is not a

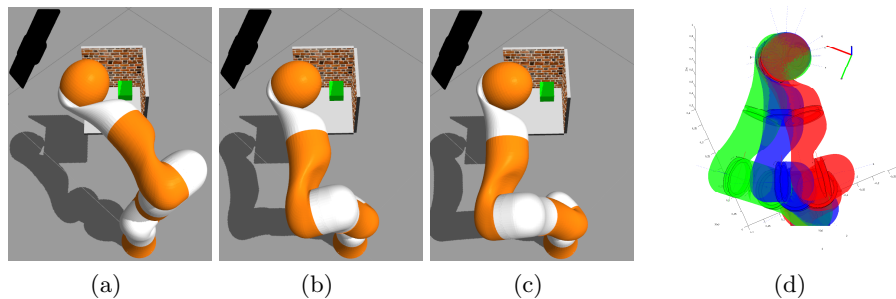


Fig. 5: Auxiliary task : using redundancy to get away from the fixed structure straight line when all sub-tasks start together.

Second experiment shows that the positioning system is compatible with other auxiliary tasks such as collision avoidance. A fourth sub-task is set with the aim of keeping the robot away from the structure. This is done simply by applying a positive angular speed on one joint. The KUKA LWR4+ is a redundant robot, the previous experiment fixed only 6 DOFs while the robot has 7. It means that the 7<sup>th</sup> DOF was subject to external noise. By setting this 4<sup>th</sup> sub-task, the all robot is now constrained. Motion during convergence is presented in figure 5. The task sequencing scheme allows the motion until it becomes incompatible with the higher priority sub-tasks. It finally stabilizes in position shown in figure 5c. Superposition in figure 5d show that this motion brought by the last sub-task force to move all joints, but keep the precise positioning task in place.

## 5 Conclusion

In this paper, a sensor-based control approach has been described to complete assembly operations. As this operation is specified with assembly constraints, a sensor-based control task has been defined and built following these. Plane-to-plane has been primarily considered and 3D depth sensor used to get a measure of the plane equation. These informations allowed us to construct the interaction matrix to map the joint motion to the measure evolution. We used also a task sequencing scheme to handle several constraints while respecting a priority order between them. Thanks to this, this robotic assembly task was compatible with other types of constraints. Simulation has been designed to validate the concept. However, sensor has been considered as a perfect sink, without taking into account noise and possible occlusions.

Future works will consider firstly the force control, allowing the contact establishment between structure and object following the task function approach. Secondly, occlusion related problems will be tackled with the use of several redundant sensors and an improved management of task priorities between all sinks. Finally, the concept needs to be tested with noisy sensors to check if the improved precision objective is reached.

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