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Robotic Demonstration for Assembling and Inspection of a Reticular Structure

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Abstract

This paper describes a set of robotic experiments performed in the frame of a work currently in progress on the ROSED laboratory testbed. The RObotic SErvicing Demonstrator, to be installed in the Space Robotics Center (CRS) at ASI "Centro di Geodesia Spaziale" plant in Matera, aims to demonstrate the capabilities of two robotic arms and a stereoscopic vision system to automatically assemble a complex structure and inspect it in tele-operation.

The paper describes the two basic demonstrations:

- automatic assembly performed by two co-operating arms exploiting data coming from Force & Torque sensor during in-contact operations.
- close visual inspection performed by a robotic arm in computer assisted tele-operation, using the geometric model of the environment measured by a stereo vision system.

1. Introduction

The idea behind this work is to demonstrate the capability of a robotic system to autonomously perform complex assembling operation and to support a remote tele-operated inspection of the assembled structure. This is done using the ROSED Test-Bed (see Figure 1) whose kernel is a couple of conventional industrial robotic systems. Each arm is equipped with a gripper and Force and Torque (F/T) sensor, and its control SW has been integrated with the SPARCO SW (SPAce Robot COntrol, a project endowed by ESA in order to develop the basic robot control system for future space research programs and experiments). One of the arms is also equipped with a stereoscopic vision system on the wrist. SPARCO implements the impedance control, which is suitable to allow the robots to accomplish tasks in which there is contact with the environment.

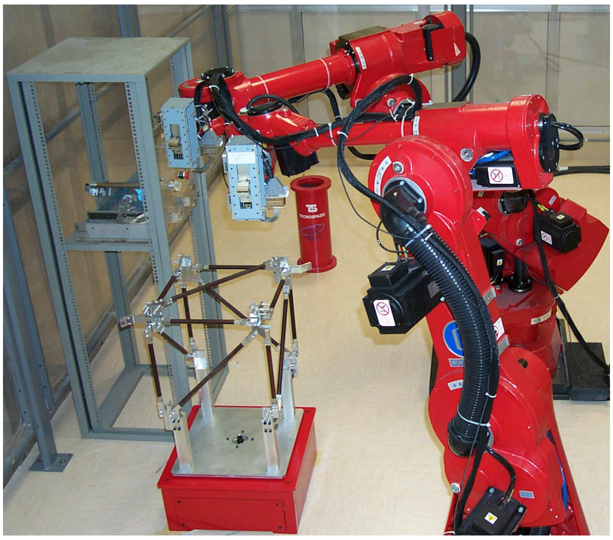

Figure 1: ROSED Test-Bed

The target of the experiments is to make the two above robots able to autonomously assemble a cube as basic item of a truss and support the operators' inspection of the assembled cube. Each face of the cube to be assembled is a square with a diagonal link. The edges of the square and the diagonal link are made of cylindrical rods: they are linked to each other through nodes which are placed at the vertices of the square.

2. Experiment layout

2.1 Robotic system description

The manipulator arms involved in the test-bed are commercial COMAU SMART S2 and S4, each driven by a C3G Plus Standard controller. The control unit is based on several processing boards connected among them via a VME bus: the robot CPU (RBC) is in charge of user's interface (I/F) handling, program translation and interpretation; inverse kinematics, trajectory generation and interpolation are demanded to the Servo CPU (SCC1). A BIT3 bus-to-bus adapter connects the

C3G VME bus and an external PC bus in order to allow data exchange between C3G and external PC.
The programming language adopted for this controller is PDL2, a Pascal-like language that provides powerful motion control instructions, multitasking, primitives for digital I/O handling and serial line I/F.
The extension for SPARCO is given by an additional SCC board (SCC2) which computes Cartesian set-point correction according to impedance algorithm control scheme. Each arm is provided with a commercial ATI F/T sensor, whose data is made available to SCC2. The C3G can also work in a modality called ‘Open Controller’: the normal C3G control flow is “cut” in order to allow an external SW running on the PC connected to the C3G to control the arm movement according to custom control algorithm. In the Open Controller modality the PC reads a set of internal data from the C3G, process them according to the foreseen algorithm and sends them back to the C3G which actuates them.
C3G provides RS232 I/Fs: they are exploited to allow communication to End Effector (EE), to provide standard user I/F running on a PC and to communicate via Kermit protocol with another PC.
To aid truss assembling, the truss base is mounted on a rotating platform.
In the current test-bed implementation a dedicated Operator Interface for tele-operation (based on a PC connected to the C3G running in ‘Open Controller’ modality) commands the trajectory of the robot to the C3G controller in resolved Cartesian co-ordinate motion with respect to the objects in the environment. The Operator Interface evaluates the robot trajectories using the information from a unique non-contact stereoscopic measuring system, mounted on the wrist of one of the two manipulator arms, which provides real-time 3D co-ordinate measurements of visible object points during close visual inspection phase.

2.2 The SPARCO approach

Aim of SPARCO is to provide a robotic system with a set of functionality to deal with operations in which contact between EE and environment is involved and forces are generated due to uncertainty of the environment. The adopted control concept is the impedance control, aiming to assign a relation between such forces and displacement of EE w.r.t. the nominal desired position. During in-contact tasks, the control goal is to make the EE behave like a mass-spring-damper system, whose parameters can be arbitrarily specified. This is achieved calculating a correction in the Cartesian space prior to inverse kinematics and through an outer control loop independent from the inner one in charge of position control at joint level.

According to the CDM (Control Development Methodology, the ESA standard for Automation & Robotics development), the definition of this control concept followed the identification of a basic set of robotic operations called TASKS such as OPEN, CLOSE, INSTALL, REMOVE, ACTUATE FORCE. Tasks are in turn decomposed into a sequence of ACTIONS, being an Action uniquely mapped to a well precise control concept (pure position control such as DISPLACE TO or F/T control such as INSERT). The modularity of this approach allows the user to extend, according to the needs of the new application, the task and action library. This modular approach has been exploited to add the new tasks HOLD and CONNECT which where required by the peculiarity of the truss assembly.

First, an Activity Analysis is performed to identify the new needed Tasks/Actions in terms of attributes (i.e. formalisation of user requirements such as initial/termination conditions).
The Preparation phase is the next step and is split into two sub-phases:

- code preparation (in PDL2 language) of Action and Task;
- SPARCO database preparation: it stores the whole information relevant to the work-cell layout.

In the SPARCO database the World Model is provided as a geometrical description of the environment, in particular of the subjects to be manipulated. This information is mainly given by means of frames. At manipulator level programming, frames represent a logical solution for describing interrelations among the objects, in which the robot can be considered only as a means to reach a desired target position.
World model is defined hierarchically so that frames logically grouped can be expressed w.r.t. a frame defined in the upper level: subjects are logically grouped in facilities, so that a parameterisation of tasks and actions is possible.

Table 1 summarises all the relevant frames. With each element (i.e. facility) of the workcell a Facility F frame is associated. F frame is defined w.r.t. to the robot base frame (${}^{B}T_{F}$). Relative to the F frame, the location of associated objects is described by means of Objects O frames (${}^{F}T_{O}$). On_pose and Off_pose frames represent the initial and the final position of the work piece frame P, being the P frame the location (${}^{O}T_{P}$) of a well specified point affixed to the object to be manipulated. The meaning of initial and final position is strictly related to the status of a subject (another variable stored in the database), which indicates also which task can be executed (for example, if the status is ‘full’, only the REMOVE_FROM Task can be executed).

Approach and Grip frames are expressed relative to the P frame.

The SPARCO database is designed so that tasks which undo each other effect can be thought as the reversal sequence of actions of the other, so the same set of data is used for both tasks. The database is updated at the end of each Task or Action in order to reflect the new status of the environment. The OPEN Task (of a drawer, for example) is split into the action sequence reported in Table 2 (note that SLIDE is considered terminated only when the force due to drawer stroke-end is sensed). Simply switching On_pose and Off_pose, the database is ready to be used by the CLOSE Task (of the same subject), which has the same structure.
Another couple of dual tasks is REMOVE_FROM / INSTALL_IN (see Table 2): the action sequence is slightly different due to the fact that the object shall respectively remain attached or detached at the end of the task. However, the concept related to the definition of frames associated to initial and destination position is still the same.

2.3 Truss mechanical description

Each element of the TRUSS was designed with more than one goal:

- to enable its manipulation from the robot
- to be light weight
- to have a high modularity

The result has been that the entire TRUSS is based on three items:

- Node
- Lateral Rod
- Diagonal Rod

Nodes and rods interface between them via two pegs mounted on the node which have to slide into holes placed at the end of the rod (see figure 2)

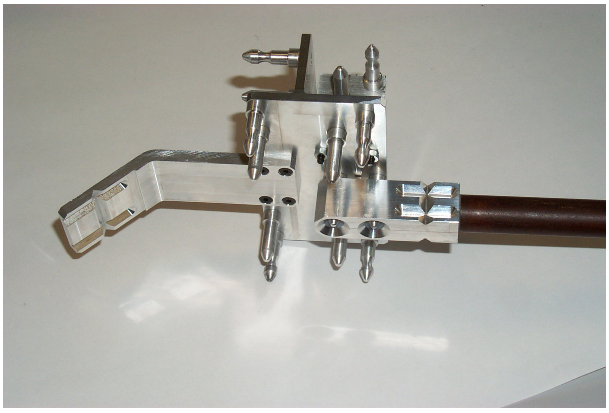

Figure 2: Node and rod

To ensure rigid connection, a locking mechanism triggers at the end of insertion. To enable their handling by the robots, rods and nodes have been designed with a suitable mechanical interface which fits with the EE.
Particular effort has been put to have the structure symmetric: when the cube is mounted, all the lateral faces appear equal, and this suggests the design of an iterative algorithm.

2.4 TVT subsystem description

The TV-Trackmeter system (TVT) is a non-contact (stereoscopic) measuring system that provides real-time 3D coordinate measurements of visible object points with light contrast of adequate level.

The remote sensor of the system is the TVT Imaging Unit (IU), fitted with video cameras, lenses and mounted between the wrist flange and the end effector of one of the ROSED arms (see figure 3).

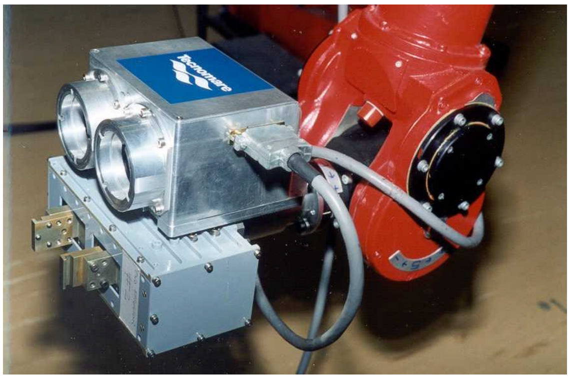

Figure 3 - The TV-Trackmeter on a ROSED arm

The TVT Processing Unit (PU), based on a SUN UltraSparc workstation, provides image processing and a graphical user interface for the Operator (see figure 4).

The TVT workstation interfaces with the cameras' video signals via a couple of SNAPPER-8 frame grabbers, which creates digital mappings of the left and right cameras' images.
The images taken from the scene can be temporarily frozen and the 3D-coordinates of each single point or the distance between any two points or the area mapping can be provided.
Using gray-level (luminance energy levels) comparison of the left and right camera images, the TVT workstation performs pattern recognition by matching the two images, obtaining the X_{left}, Y_{left} and X_{right}, Y_{right} pixel positions of corresponding points in the two images. Software routines performing triangulation can then establish the points' X,Y,Z orthogonal coordinates with respect to the IU.

Thus the orthogonal coordinates of points with sufficient contrast are determined and 3D coordinates of single points or 3D-distance measurement from point to point or 3D mapping may be obtained.

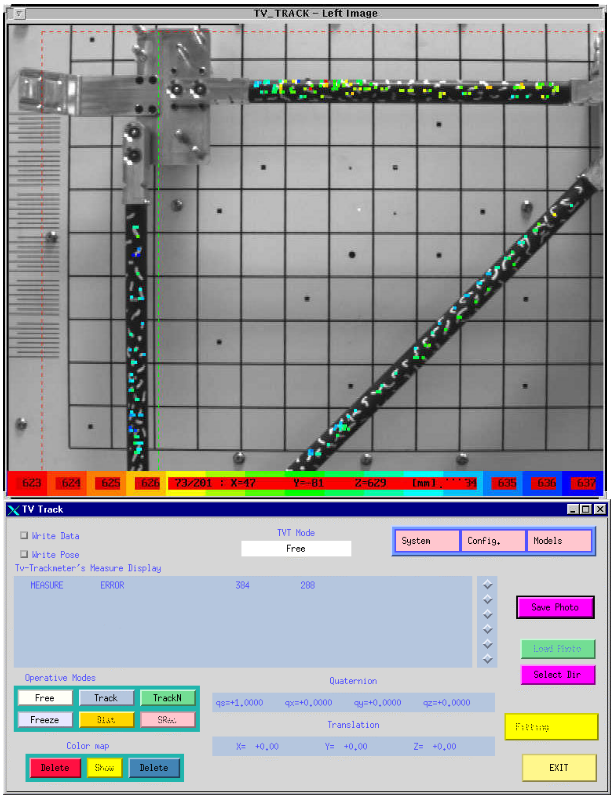

Figure 4 - The TV-Trackmeter User Interface

In case of 3D mapping, the TVT can also interpolate the measurements over the surface of the object and obtain a geometrical reconstruction of the scene, by using an iterative statistical fitting method.
The first stage of this fitting is “scene mapping”, a process where a selected part of the observed scene (the object) is scanned and the coordinates of measurable points are temporarily stored as a mapping of that object’s surface.
In the second stage of “best fitting”, this mapping is compared, if needed, with object geometrical information to give an indication of the fitting accuracy and also derive the object’s orientation with respect to the IU. This geometrical information is provided either by measurements made by the TVT at significant points on the object (corners if a quadrilateral, or axis if a cylinder) or by so called *a-priori* known (i.e. previously determined) information coming from the Operator.

This fitting provides data on the object’s position and orientation with respect to the TVT stereo cameras’ reference frame. In ROSED applications the measurement of the object’s pose is sent via serial line to the Operator Interface PC which is able to communicate with C3G controller and to modify its normal control flow through a set of SW libraries. The object pose information makes the PC capable of moving the EE of the ROSED arm relative to the reconstructed object.

Digital recording of stereoscopic images on the TVT PU hard-disk is provided, enabling post-processing without loss of resolution or accuracy.

In order to update and monitor on-line the pose of an object, the Operator sets the “tracking” operating mode of the TVT and selects one or more (up to six) points of the object in the scene. They are automatically tracked by the system in the live TV frames, thus providing to the robot Control system the pose measurement of the object (even if moving in the scene) with respect to the moving end effector.

In order to allow for easy integration with robot control systems such as the ROSED Controller, the TVT system has been designed with standard interfaces through both serial line and Ethernet TCP/IP connections. A robot control system connected to the TVT is provided with:

- measurement of workspace for precise tele-manipulation.
- tracking of objects for close positioning purposes
- Scene Reconstruction data (object fitting for cylinders, planes, quadrilaterals, points)
- Photogrammetry measurements and mappings.

3. Truss assembly

In order to be assembled, nodes and rods have to be taken from the relative repositories by the two arms. Stable supports for the cube to be built are four columns, at top of which four nodes are already mounted. The columns are attached to a base which can be rotated of steps of 90 degrees through a motor connected and driven via I/O signal by S2 arm controller. Such revolving base allows the two robots to operate always in the same way to build the lateral faces of the cube within the working space constraints. Therefore the Activity Analysis has identified a set of logical operations (called compound tasks) in which the overall robotic system (2 robots and rotating base) are able to modify the test-bed layout from the initial to the final condition. Columns and vertical faces are numbered anti-clockwise. Vertical edge 1 (2) is, regardless of base rotation, the closest to S2 (S4) arm.

Face n is between edge n and either edge n+1 (if n<4) or edge 1 (if n=4).
A small set of parametric compound tasks (summarised in table 3) was implemented. A sequence of such compound tasks operating on the same edge and face with different parameters leads, as briefly demonstrated in table 4, to the assembling of the cube. VEn stands for Vertical Edge n, VFn stands for Vertical Face n, TF stands for Top Face. For each row, the 'X' mark in a column means that the related item is assembled at the end of the correspondent compound task. The details of the compound tasks are described in table 5.
Critical operation in the above-defined compound tasks is the connection of a rod to a node: a high force has to be exerted to lock the connection. This is not always possible since the force applied by the robot results in the structure displacement, due to its flexibility, instead of exceeding the friction of the locking mechanism.
The HOLD task was defined to deal with this, so while one of the two robots transports and inserts either the rod or the node the other holds the structure to avoid its displacement.
In the Vertical_Edge_Assemble, S2 and S4 robots take respectively a node and a rod from the repositories; S4 installs the rod in the lower node on column 1, then goes to grasp and hold the other end of the rod, so that S2 can insert the node into it.

In the Vertical_Face_Assemble, a rod must be linked to two nodes, one for each end (for example the diagonal link): in this case, first a rod is transported and inserted into a node that is held by the other robot. Then, the other end of the rod has to be connected to the remaining node by pushing the rod (which is not completely inserted and locked) while the other robot holds the node. The same operation is repeated for the other end to be sure that the locking mechanism has triggered.
The co-operation strategy used during the truss assembly is based on a synchronisation method that uses *rendez-vous*. The idea behind rendez-vous is that activities following it must be started simultaneously by the two robots. So each robot independently executes its own assembling sequence (whose items are compound tasks, tasks, actions and rendez-vous) and when it arrives to a rendez-vous, it stops itself and waits for the other robot to catch up the correspondent rendez-vous. Only when both robots are at the rendez-vous they can proceed with the next operation. So neither of the two robots is the master of the assembly operations: each robot proceeds with its own task sequence and a co-operation is established when needed, according to the best solution for the particular case.
Collision between the two robots is avoided by logically dividing the free space into a SMART S2 operation area, a SMART S4 operation area and a COMMON operation area. Whenever a robot is entering the common operation area there should be the guarantee that the other robot is in its own operation area. Such guarantee is obtained handling the rendez-vous at compound task level.

4. Tele-operated visual inspection

In the current ROSED implementation the TVT measurements are used to assist the Operator in the inspection of the assembled truss structure. The visual inspection is performed using the images from one of the TVT cameras and moving it (connected to the arm wrist) with a joystick. A dedicated Operator Interface for tele-operation is used to command the arm motion in resolved Cartesian co-ordinate mode. During the motion of the TVT cameras following the surface of the truss components, the Operator commands (using the joystick) the desired speed values of the TVT cameras along a virtual surface whose points are at the same distance from the structure. The orientation of the TVT cameras is automatically maintained perpendicular to the object surface or maintained with the attitude set by the Operator.
Another interesting operational mode of the TVT, which can be used for future integration with the two-arm robotic system, is the "tracking" function. It permits to select one or more points which are automatically tracked by the system in the next TV frames, thus providing 3D co-ordinates of moving points or the position and attitude of a moving object with respect to the arm. The tracking data of such an object can be used to close the dynamic positioning of the end effector with respect to it.

5. Conclusion

The ROSED Test-Bed proved to be suitably thought and designed to successfully complete the TRUSS cube assembling but also highlighted the critical issues in this kind of activities. Impedance control, combined with ad-hoc mechanical design, proved its effectiveness to deal with uncertainties during in-contact operation. The modular structure of the control system allowed a breakdown of the TRUSS assembly in independent activities involving different competencies (impedance control tuning, mounting sequence strategy planning and many others). However, mechanical design is not sufficient to enable the impedance control to deal with positioning uncertainties cumulating during assembling of bigger structures then a cube.
The result obtained in the tele-operation suggests that a further integration of the robotic controller with the

TVT vision system may lead to automatically obtain the position and orientation of elementary objects of the truss structure during operations, thus reducing the environment uncertainty within a range suitable for impedance control. This would consequently enable the robot Controller to assemble the truss using an environment a-priori model less precise than the currently used one.
These new capabilities can be easily added since allowed by the modular design of ROSED that is based on the SPARCO approach.

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NAME	NOTATION	DESCRIPTION
Robot Base *B*	--	It is the frame associated to robot base
End-point *E*	${}^{B}T_{E}(\boldsymbol{q})$	It is the frame associated to the robot flange
Tool-centre point *T*	${}^{E}T_{T}$	It is associated to the robot gripper
Facility *F*	${}^{B}T_{F}$	It is associated to an item of the work-cell (e.g. rack)
Object *O*	${}^{F}T_{O}$	It is associated to an item of the facility (e.g. drawer)
Work-piece *P*	${}^{O}T_{P}$	It is associated to an item of the object (e.g. drawer bottom)
Approach_pose *Appr*	${}^{P}T_{Approach\_pose}$	Location from which the arm approaches the object to grip it
Grip_pose *Grip*	${}^{P}T_{Grip\_pose}$	Location in which the TCP is at grasping

Table 1: SPARCO frames

OPEN/CLOSE tasks	REMOVE_FROM	INSTALL_IN
DISPLACE TO stand_by_pos (stored in the DB)	DISPLACE TO	DISPLACE TO
MOVE_ALONG path_of_nodes (stored in the DB)	MOVE_ALONG	MOVE_ALONG
MOVE_LINEAR_APPROACH (to Approach frame)	MOVE_LINEAR_APPROACH	MOVE_LINEAR_APPROACH
APPROACH (to Grip frame)	APPROACH	APPROACH
ATTACH	ATTACH	--
SLIDE (move P frame to off_pose)	EXTRACT	INSERT
DETACH	--	DETACH
RETRACT (to Approach frame)	RETRACT	RETRACT
MOVE_ALONG path_of_nodes	MOVE_ALONG	MOVE_ALONG
DISPLACE TO stand_by_pos	DISPLACE TO	DISPLACE TO

Table 2: Task breakdown

COMP. TASK	INITIAL CONDITION	FINAL CONDITION
Vertical_Edge_Assemble <n>	One rod and one node in the respective repositories.	Vertical edge assembled on column <n> (lower end of the rod connected to already installed lower node; upper end connected to new node).
Vertical_Face_assemble <n>	Two vertical edges assembled in column <n> and <n+1>; One lateral and one diagonal rod in their repository.	Vertical face assembled (3 edges and diagonal link connected to lower left and upper right vertices).
Top_Face_Assemble	four vertical faces assembled; One diagonal rod in its repository.	Top face assembled (diagonal link connected horizontally).
Base_Rotate	None.	Base is rotated of 90 degrees (former column n is now column n+1).

Table 3: Compound tasks

Step id	COMP. TASK	VE1	VE2	VE3	VE4	VF1	VF2	VF3	VF4	TF
1	Vertical_Edge_Assemble 1	X								
2	Base_Rotate		X							
3	Vertical_Edge_Assemble 1	X	X							
4	Vertical_Face_assemble 1	X	X			X				
5	Base_Rotate		X	X			X			
6	Vertical_Edge_Assemble 1	X	X	X			X			
7	Vertical_Face_assemble 1	X	X	X		X	X			
8	Base_Rotate		X	X	X		X	X		
9	Vertical_Edge_Assemble 1	X	X	X	X		X	X		
10	Vertical_Face_assemble 1	X	X	X	X	X	X	X		
11	Base_Rotate	X	X	X	X		X	X	X	
12	Vertical_Face_assemble 1	X	X	X	X	X	X	X	X	
13	Top_Face_Aseemble	X	X	X	X	X	X	X	X	X

Table 4: Cube assembling sequence

Compound Task	S2 phase	SMART S2 task	SMART S4 task	S4 phase
Vertical_Edge_Assemble	1	Remove node from repository	Remove rod from repository	1
	2	Rendez_vous	Rendez_vous	2
	3	rotate_base		
	4	Rendez_vous	Rendez_vous	3
			Install rod in lower left node	4
			Go to hold left rod by grasping upper end	5
	5	Rendez_vous	Rendez_vous	
	6	Install node in left rod upper end	Keep holding	
	7	Rendez_vous	Rendez_vous	
			Return from hold	
Vertical_Face_Assemble	1	Rendez_vous	Rendez_vous	1
	2	Remove rod from repository	Go to hold by pushing upper right node	2
	3	Rendez_vous	Rendez_vous	
	4	Install horizontal rod in upper right node	Keep holding	
	5	Rendez_vous	Rendez_vous	
	6	Go to hold upper left node	Return from hold	
		Rendez_vous	Rendez_vous	3
		Keep holding	Connect upper left node/horizontal rod	4
		Rendez_vous	Rendez_vous	5
		Return from hold	Go to hold by pushing upper right node	6
	7	Rendez_vous	Rendez_vous	
	8	Connect upper right node/horizontal rod	Keep holding	
	9	Remove diagonal rod from repository		
	10	Install diagonal rod in upper right node		
	11	Rendez_vous	Rendez_vous	
	12	Go to hold by pushing lower left node	Return from hold	
		Rendez_vous	Rendez_vous	7
		Keep holding	Connect lower left node/diagonal rod	8
		Rendez_vous	Rendez_vous	9
		Return from hold	Go to hold by pushing upper right node	10
	13	Rendez_vous	Rendez_vous	
	14	Connect upper right node/diagonal rod	Keep holding	
	15	Rendez_vous	Rendez_vous	
			Return from hold	
Base_Rotate	1	Rendez_vous	Rendez_vous	1
	2	rotate_base		
	3	Rendez_vous	Rendez_vous	2
Top _Face_Assemble	1	Rendez_vous	Rendez_vous	1
	2	Remove diagonal rod from repository		
	3	Install diagonal rod in back left node		
	4	Rendez_vous	Rendez_vous	2
	5	Prepare Connect back left node/diagonal rod	Prepare Connect upper right node/diagonal rod	3
		Rendez_vous	Rendez_vous	
		Connect back left node/diagonal rod	Connect upper right node/diagonal rod	

Legenda:

lower left node	Node: 1	Face: 1
lower right node	Node: 2	Face: 1
upper right node	Node: 3	Face: 1
upper left node	Node: 4	Face: 1
back left node	Node: 3	Face: 3

- The HOLD task is spliced in 5 sub-tasks (go to hold, rendez_vous, keep holding, rendez_vous and return from hold)
- The CONNECT in co-operation in 3 sub-tasks (Prepare to connect, rendez-vous, connect)
- Background colours have been used to mark distinct compound tasks
- Vertical bold lines group sub-tasks in the associated tasks HOLD and CONNECT
- Rendez-vous are represented through black lines just below a pseudo-task called "rendez_vous"

Table 5: Compound Task detail