

SIMULATION, ANALYSIS AND EXPERIMENTS OF ON-ORBIT ASSEMBLY BEHAVIOR ON FLEXIBLE STRUCTURE BY COOPERATIVE ROBOTS

Hiroshi Ueno¹⁾, Vickram Mangalgi²⁾, Steven Dubowsky²⁾,
Takeshi Sekiguchi¹⁾, Mitsushige Oda¹⁾, Yoshiaki Ohkami¹⁾

1) Institute of Space Technology and Aeronautics
Japan Aerospace Exploration Agency (JAXA)
2-1-1, Sengen, Ibaraki 305-8505, JAPAN
(E-mail : ueno.hiroshi@jaxa.jp)

2) The Field and Space Robotics Laboratory
Massachusetts Institute of Technology
77 Massachusetts Ave., Cambridge, MA 02139 USA

Abstract

This paper describes the planning and control of the cooperative space robot systems used to assemble large-scale flexible structures such as Space Solar Power System. One of the major challenges in the assembly process would be the handling of dimensional mismatch between the two structures to be joined. To track the vibrating structures before the grasp, we have demonstrated the algorithms for the visual servo in the wide area with motion prediction using cooperative robots on the ground testbed. After grasping the structures, we have simulated the forced assembly planning methods using cooperative robots to compensate for distortion.

1. Introductions

The International Space Station (ISS) has been under construction in orbit since 1998 and is a great example of gradual assembly, piece-by-piece, of large-scaled structures (LSS). On-orbit assembly will become one of the key technologies for future missions such as the space solar power system (SSPS) and large space telescopes.

The complex assembly for the ISS construction, based on a combination of extra-vehicular activity (EVA) and teleoperated robotic arms, uses the skills

and experience of both trained astronauts and ground support [1]. For the study of assembly of the large structure on ISS, relatively rigid mirror assembly with high accuracy operation is considered [2]. However, there is not much assembly missions aimed at light-weight structures where flexibility becomes a major effect of system characteristics.

This paper is focused on the planning and control of the cooperative space robot systems used to assemble Space Solar Power System (SSPS). The next section identifies potential challenges to the large structure assembly process in space. We discuss and analyze the dimensional mismatch between the two structures in the assembly process in third section. Before grasping the lightweight structure in assembly process, the cooperative robot systems that track the vibrating structures are introduced in the fourth section. In the fifth section, we demonstrate the possible solution for them by the wide-range visual servo and the flexible motion estimation. After grasping the structure, the cooperative robot system is required to joint the structures. The sixth section describes the forced assembly methods using cooperative robots to compensate the dimensional errors between the two structures to be joined.

2. Technological Challenges in Construction

One of the SSPS concepts developed in JAXA comprises very large space structures whose dimensions are several square kilometers, as

illustrated in Fig. 1. Due to the limitations of the launch vehicle capability, only restricted-mass and appropriately stowed structures are transferred to orbit. Therefore one-orbit assembly of light-weight structures is inevitable to construct the SSPS. Simultaneous operation of multiple robots becomes quite feasible and may be even essential for efficient assembly using repeated tasks and for minimum duration high-lighted by economical requirement[3].

Several technological challenges must be overcome in order to assemble and maintain the SSPS. Assembly and maintenance tasks include: (1) transportation and handling of inertial components, (2) handling and checking of deployable or pre-assembled structures, (3) locomotion on and suppression of flexible structures, (4) repair and exchange of large structures and components, and (5) inspection and diagnosis of structures. These tasks are preferably performed autonomously, with minimum operational resources.

From these tasks, we identify several challenges to the technology.

- (a) Handling of a variety of structures
- (b) Transportation on flexible or inflatable structures
- (c) Capture and connection of deployable and pre-assembled structures
- (d) Autonomous detection of structure malfunctions
- (e) Limited time required for the tasks

This paper provides possible solution for the above (c) on task (2).

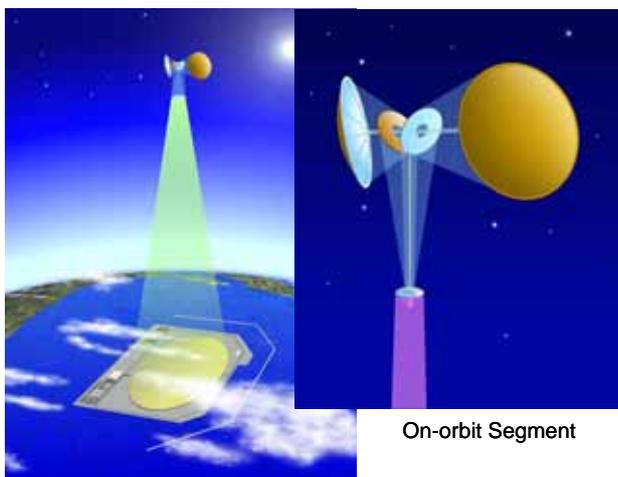


Fig. 1 Concept of Space Solar Power System

3. Analysis of Flexible Structure Assembly

The static and dynamic effect on a typical large space structure is analyzed by using finite element models and the deformation that the structure will undergo is predicted due to thermal and vibration effects in space.

The varying and harsh thermal conditions in space will affect the large structures by changing their dimensions and causing warpage. These effects have been studied and modeled on some representative structures using finite element analysis. The goal here is to provide an estimate of such dimensional changes.

To analyze a realistic assembly process, it is necessary to develop a model for the thermally warped base truss having dimensions of about 200m x 200m and made up of these smaller triangular elements by using the property of the currently available materials and structure. For a structure of this size, the maximum deformation was observed to be approximately 1 m as shown in Fig. 2.

The large space structure finite element model can be used to perform vibration analysis. This is necessary to determine the nature of vibrations that may be induced by contact with robots. A finite element model of the LSS was set up and the natural frequencies and mode shapes were determined as illustrated in Fig. 3. Any unbalanced force applied to the structure may cause large displacements which may not damp out quickly. Knowledge of the structure mode shapes is important to prevent their excitation and thus prevent unwanted vibrations. This information will also impact assembly techniques where timing of the operation is important.

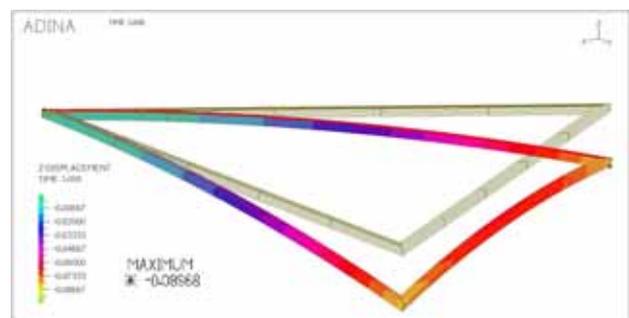


Fig. 2 Thermal Deformation of a Triangular Structure

The assembly process involves grasping connection points on the mating trusses with manipulators and forcing them together by the combined deformation of both trusses. The following tasks need to be carried out for the assembly process:

- Estimation of the magnitude of mismatch – This can be obtained from the previous analysis of thermal deformation
- Estimation of forces required
- Development of sensing techniques to determine actual locations of mating points

Using multiple robots is a viable solution to this problem. The various tasks involved in the assembly process thus would be carried out by teams of robots operating cooperatively. Proposed solutions would take into account this distributed sensing and actuation. Multiple robots would estimate the structure’s dimensional mismatch using their vision sensors and perform deformation using their actuators. The robots would perform the tasks subject to the following constraints:

- Shape/size of the structures
- Power consumption
- Safety of approach paths
- Communication delays between robots
- Sensing delays

4. Methods of Tracking Flexible Structures

Based on the scenario of constructing a large space structure, it is assumed that one of the edges of the deployable or pre-assembled structures is connected to the base structure, while the other sides of the structures are free floating, to be assembled as illustrated in Fig. 4. The cooperative robot system may be essential to search the wide area of the structure vibration, to predict the significant motion, to capture the structure, and to connect the structures together on the flexible platform.

To capture the structure, the robot must estimate and predict the motion of the flexible structure. In most cases, however, a robot is not large enough to follow the significant motion of the flexible structure. Therefore another global sensing robot is needed. This sensing robot, mounted on the vibrating environment, measures relative position and orientation of the flexible beam with respect to the capturing robot. The two on-orbit robots share information through the computer network.

To track the flexible structure, each robot visually estimates the vibration, motion, and executes control servo. Fig 5 depicts the control scheme of motion estimation and visual feedback. The sensing robot utilizes the visual measurement of the structure in relation to the capturing robot, while the capturing robot utilizes the visual images of the structures on both robots. The motion-estimation method uses both the visual measurement and the robot positions.

4.1 Visual Feedback by Cooperative Robots

In general, on-orbit assembly by space robots relies on a hand-eye camera to measure relative distance between the robot end-effector and the object to be grasped, and to guide the end-effector to the object using sensor feedback. In assembling the SSPS where robots are attached to the flexible and



Fig. 3 Various Vibration Modes of a Typical Large Truss

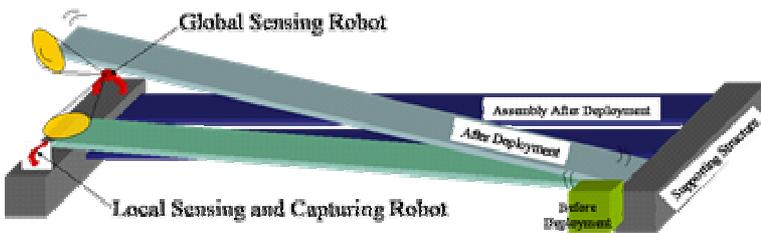


Fig. 4 Flexible Structure Assembly by Multi Robots

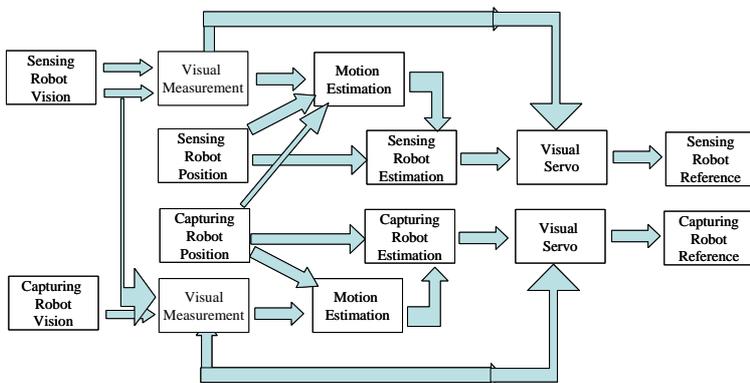


Fig. 5 Control Scheme for Flexible Structure Tracking

vibrating base, broad fields of view are required to measure the large relative motion of the vibration. Therefore, the hand-eye camera of a single robot may not provide a broad enough view to assemble such structures.

The multiple-robot system may solve such a situation by combining the camera information to share the view of the shaking motion. The multiple-view system could also detect malfunctions of other sensors and compensate for measurement errors.

4.2 Estimation of Vibrated Motion

A visual feedback system to follow the moving target may not be enough to capture the target due to the lag time between the measurement of the camera and the actual motion of the robot. Therefore we require another mechanism, in addition to visual feedback, to precisely follow the moving target. Motion estimation could be one solution to reduce the errors caused by the time delay, and may be feasible due to the fairly predictable vibrated motion.

The goal in estimating the vibration motion is to identify the dominant parameters of the vibration and to predict the motion of the vibration in the near future to compensate for it. Because low-frequency vibration may have less damping in general, continuous vibrating motion is expected for large flexible structures, and prediction of the motion is useful.

To predict the motion, we use the data of the time history for both the robot motion and the vision measurement. The motion data is slightly corrected through interpolation so that the robot time-stamp is exactly the same as the vision

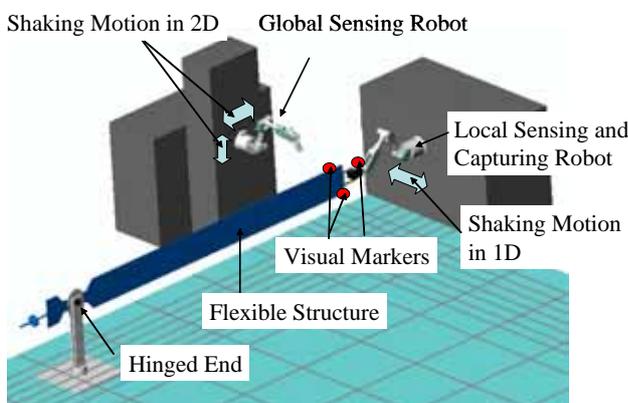


Fig. 6 Illustration of Ground Testbed

time-stamp. By using the time history data of both, we can identify the relative motion of the target structure's vibration in relation to the shaking base of the robot. The identified parameters of the vibration are a bias of the vibration, amplitude, and phase of the vibration under the known frequencies.

5. Tracking Experiments on Ground Testbed

5.1 Ground Testbed

We have developed a ground testbed to study the feasibility of assembling the flexible structures. The testbed consists of a flexible structure and two robots on mobile bases, as illustrated in Fig. 6. The flexible structure represents the characteristics of the deployable or pre-assembled structure where one of the ends is fixed at the base while the other ends are free. The flexible structure is hinged lengthwise at the base and can passively rotate except in the direction of torsion. The flexible structure is 4 m long with a 0.15 Hz first-mode natural frequency, which corresponds to a 1/10 scale model of the actual system. The handle (to be grasped by the robot arm) and two visual markers (to be measured by the hand-eye camera) are at the tip of the free end of the structure.

One robot is used for sensing the global structure, while the other is used for local sensing, and for tracking the structure. Each robot is an industrial-based robotic arm, 1 m in length, with seven degrees of freedom. Attached at the end of each robot are the end-effector and the hand-eye camera. They, respectively, grasp the structure and measure relative position and orientation of the flexible beam with respect to the grasping hand.

Each robot is mounted on a mobile base to imitate the vibration environment on the flexible platform on orbit. During the experiment and isolated from the robot control, the pre-programmed shaking motion is executed. The vibration parameters can be selected from 100 to 200 mm p-p with 0.10 to 0.20 Hz sinusoidal vibration in one or two dimensions.

Table 1 Time Lag on Ground Testbed

Time Lag	Experimental Results		
	Vision Process Time Lag	Robot Control Process Time Lag	Main Control Process Sampling Time
Averaged Time[sec]	0.79	0.15	0.12

5.1 Tracking Experiments

We conducted two types of experiments before applying the algorithm to the testbed. The first experiment measured the responses and lag time for the total system from taking the image to receive the data from the robot. The time is measured on the main control process. Table 1 shows the time delay presumably due to the vision calculation process and the computer network communication.

The second experiment is the motion estimation without control to confirm the feasibility of the estimation algorithm. The algorithm utilizes both the time history of the robot position and the vision measurement. Twenty historical data sets provide better practical results when compared to ten and fifty data sets. The estimation parameters are calculated at each sampling time. The motion in the near future is predicted based on the parameters. The predicted time is set to 1 sec, which corresponds to the total time delay of the ground test bed as measured in the previous paragraph. The estimated motion results agree with the measurement data as seen in Fig. 7.

Based on the previous component-level experiments, we performed the total-system experiments applying the proposed methods and control scheme to two robots and two vision cameras. After the robots were shaken, both robots successfully tracked the flexible structure. The typical results are shown in Fig. 8. The left side is the vision measurement from the global camera to the local robot without controls, where the bases of both robots are vibrating in the X and Y directions. The right side is the measurement with the estimation and tracking. The global sensing robot successfully tracks the vibration of the local robot and reduces the magnitude of the vibration by half.

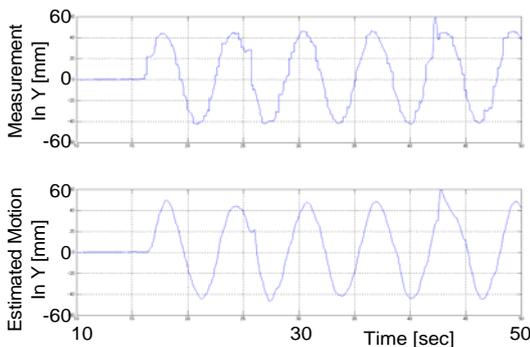


Fig. 7 Motion Estimation Evaluation

6. Jointing Methods in Assembly Process

After robots grasp structures, a typical large space structure assembly scenario would involve the joining of a small sub-structure to a much larger structure. One way to perform assembly in the wake of dimensional mismatch would be to use robotic systems to bend the warped structures into place.

6.1 Forced Assembly by Robot Manipulation

To assemble the warped structures, sufficient forces must be applied at the joints to cause the entire structure to deform temporarily to the desired shape. The forces required to deform some thermally warped structural shapes can be determined using the finite element model of LSS. Cooperative robot system would sense the position error and fit the mating objects into place. However, a variety of factors may make it impossible for direct application of force at the point of deformation, such as awkward and unwieldy shape of the structure or the robot, errors in attitude of the robot with respect to the structure and hence errors in the line of application of the forces, etc. This implies that robots would have to apply forces at some other suitable location and remotely cause deformation at the mating point. The task now is to determine the magnitude and location of these forces.

This problem can be solved by individually analyzing the deformations caused in the structure due to each candidate force. The points of application as well as force directions are chosen to take into account all the constraints. A linear system model is assumed in which the bending of the

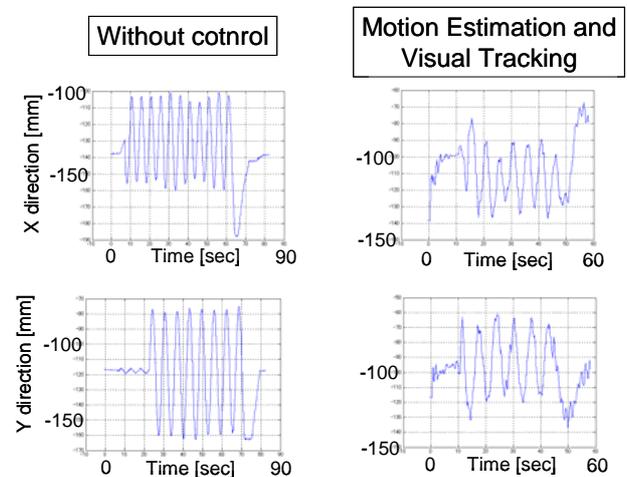


Fig. 8 Motion Estimation and Visual Tracking

structure can be represented by a transformation matrix T . This matrix relates the effect of forces applied at some specified points to deformation that is caused at certain other points of interest.

In general, a small number of robots can be used to carry out the required deformation at a large number of points leading to a distributed actuation network. Here a small force vector controls a relatively large displacement vector and the transformation matrix is not-square. This problem can be solved by using the matrix pseudo-inverse.

The results obtained have been verified by plugging back into the finite element model to determine the actual shape. This conformed to the desired shape of the truss as shown in Figure 9.

6.2 Deformation on Single Connecting Point

The problem considered here is the assembly of the basic truss framework. Hence, there is no underlying structure and connections need to be made at a single connection point per side of the small truss. In addition:

- The base truss is assumed to be much stiffer than the small truss and also has a very large mass as compared to the small truss.
- Structure misalignment occurs only due to thermal loads in the out-of-plane direction.
- The dimensional mismatch between the trusses is within the reach of the robot manipulators and the forces required for deformation are less than the maximum force that can be exerted by the manipulators.

Three points on the small truss need to be connected to three corresponding points on the base truss. The first joint connection is unconstrained and can be connected without significant forces. A triangular shaped truss having sides 200m long

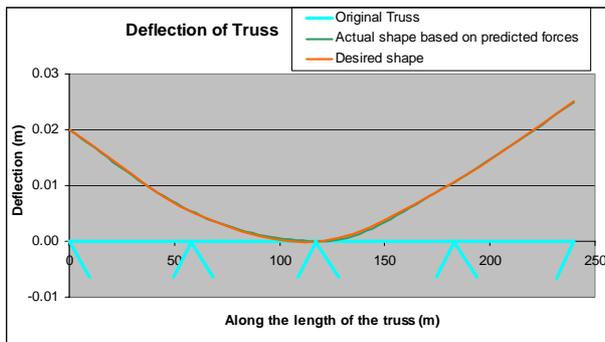


Fig. 9 Comparison of Actual Shape of the Truss Based on Predicted Forces with the Desired Shape

warps due to thermal loads in space. A model of this triangular truss was created in FEM and a thermal and structural analysis yielded a maximum out-of-plane deformation of 0.88 m at the corners of the truss. As a result, the second and third joint connections were not unconstrained. It was found that a force of 3.55 N had to be applied to bend the truss into place. This also caused a deformation at the third joint location. The total deformation at the third joint reduced to 0.73 m at this stage. A force of 5.12 N had to be applied to make the last connection in the assembly process as shown in Fig 10.

6.3 Deformation on Multi Connecting Points

In this case, the small truss needs to be connected to the base truss at multiple points along each side (See Fig. 11). This could be required, for example, in assembling a reflecting surface on to an existing framework. Truss shape is important, and hence the goal is to minimize shape error between the thermally deformed trusses. All other conditions remain the same as the single connection point case.

Assembly can be carried out if all the pairs of connection points are brought within a certain distance of each other specified by the joint tolerance. The feasible method is to bend the entire

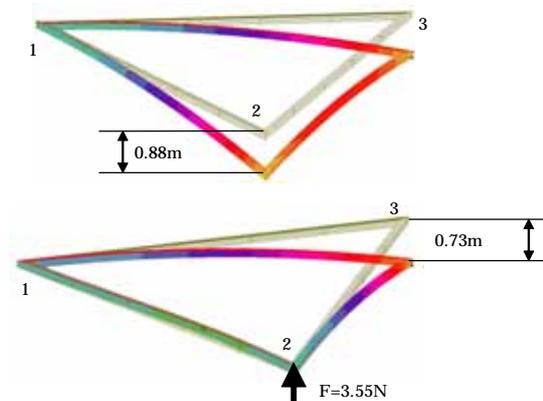


Fig. 10 Assembly Plan for Single Connection Point

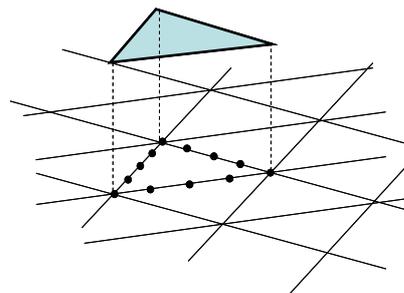


Fig. 11 Assembly with Multi Connection Points

truss to the desired shape in one step, such that the distance between the connection points is within the joint tolerance. Given unlimited number of robots working simultaneously, this is always possible. The challenge, however, is to optimize the force locations and magnitudes to use minimum resources. Since the shape of the structure is important, the root mean square deviation of points on the structure from the desired shape is used as an error measure.

Thus far, it had been assumed that the location of connection points would either be equi-distant or pre-determined, and the small truss would be bent to conform to their locations. However, in some situations such as in the construction of the huge mirror for the SSPS, the shape of the individual panels that will reflect the solar radiation will be critical and should be minimally deformed. In such situations, the location of connection points themselves can be optimally determined using the Chebyshev spacing method [5] to minimize the shape error. A Chebyshev polynomial has the property of deviating the least from zero in an interval, amongst all same-degree polynomials with leading coefficient equal to unity. Therefore, if the connection points on the truss are chosen to match with the accuracy points of the corresponding Chebyshev polynomial, then the shape error will be minimized. This principle has been applied to beam bending as shown in Fig. 12.

A Chebyshev polynomial is given by:

$$T_n(x) = h^n 2^{1-n} \cos \left[n \cos^{-1} \left(\frac{x-a}{h} \right) \right] \quad (1)$$

where, n = number of accuracy points

The accuracy points will be the optimal location of connection points. Chebyshev spacing of accuracy points has been slightly modified to match the boundary conditions in the beam-bending case.

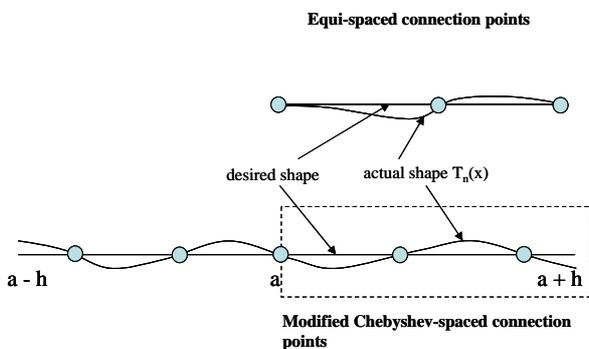


Fig. 12 Equi-distant spacing vs Chebyshev spacing

As seen in Fig. 13, the shape error indeed turns out to be lower for Chebyshev spacing of connection points as compared to equi-distant spacing.

6.4 Large Deformation on Multi Points

If assembly is performed onto an existing framework where typically there would be many connection points along each beam, the shape of the truss will be important, not just the deformation at the corner points. The goal would be to minimize the shape error while bending the truss. This problem is similar to the previous one with the additional feature of large-scale deformation.

In assembly scenarios where a specified number of connections need to be made, thermally deformed structures have to be physically bent so as to get the connection points within grasping distance of each other.

The one of approach would be to use the fact that the small truss would be connected at least to one point on the base truss. From this point, the robot could simply use its manipulators at a point where it is able to grasp both trusses and progressively perform the connections. Figure 14 shows this 'button-down' approach. The analysis for this approach would be similar to the analysis in the previous section, however with one important caveat. Since the forces would be applied closer to the fixed connection point than before, the advantage of having a significantly large moment arm (200 m in this case) is lost. For a simple beam, the beam bending relationship for forces acting in the transverse direction is given by

$$y = \frac{FL^3}{3EI} \quad (2)$$

where, y is the displacement at distance L from

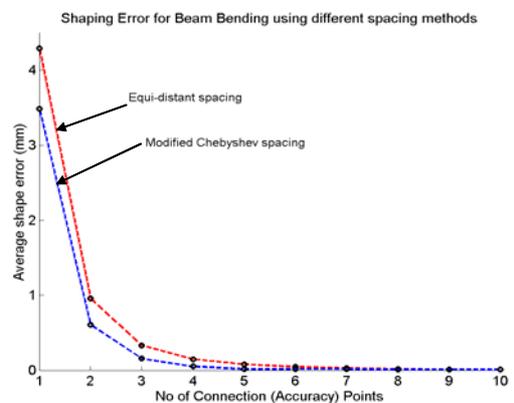


Fig. 13 Shape Error for Beam Bending

the fixed end of the beam where force F is applied. This shows that the force required for a given displacement varies inversely as the as the cube of the distance from the fixed end. The force required quickly increases beyond the capabilities of the robot manipulators.

7. Conclusion

The main focus of this paper was to identify the potential problems that may be associated with future large space structure construction and develop methods to mitigate these problems. The tasks for tracking and connecting the deployable or pre-assembled structures are analyzed and found the important influences for assembly performance.

Tracking the vibrating structure before the grasp, the cooperative robots may be required due to the large vibration. The method of tracking the flexible structure using cooperative robots on a shaking base includes the broad view of the visual servo and the estimation of flexible motion. We have successfully performed to demonstrate to track the flexible structures under the proposed methods using ground testbed.

Joining the deformed structure after the grasp, the cooperative robots may be useful to compensate the deformation. Some representative assembly scenarios involving small scale deformation were analyzed and assembly plans were recommended for them. We also dealt with the assembly scenarios involving large scale deformation.

In the nature future, we plan to study handling the flexible structures after grasp where the cooperative robot may handle the flexible structures without vibration at the end of motion.

References

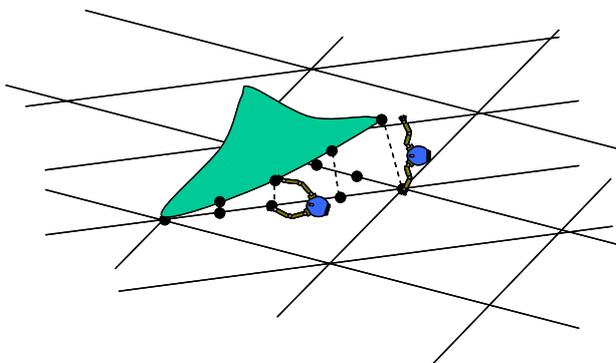


Fig. 14 Assembly with Multiple Connection Points

- [1]Phung, K. Nguyen and Michael Hiltz, "RMS Operations Support: From the Space Shuttle to the Space Station", the proceedings of the 6th international symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2001), June 2001, Montreal, Canada
- [2]R. Licata, etc., "Robotic Assembly of XEUS Mirror Sectors on ISS", the proceedings of the 7th international symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2003), May 2003, Nara, Japan
- [3]Oda, M., and Mori, M., "Stepwise Development of SSPS; JAXA's Current Study Status of the 1GW Class Operational SSPS and Its Precursor", IAC-03-R.3.03, 54th International Astronautical Congress, Bremen, German, September-October, 2003
- [4]Vickram S. Mangalgi, "Analysis for the Robotic Assembly of Large Flexible Space Structures", Thesis of Master of Science in Mechanical Engineering at the Massachusetts Institute of Technology, January 2004.
- [5]Hartenberg, R.S., Denavit, J., "Kinematic Synthesis of Linkages", McGraw-Hill Book Company, USA, 1964
- [6]Ueno, H., Nishimaki, T., Oda, M., Inaba, N., "Autonomous Cooperative Robots for Space Structure Assembly and Maintenance", the proceedings of the 7th international symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS 2003), May 2003, Nara, Japan
- [7]Ueno, H., Oda, "Assembly Robot Ground Experiments for Space Solar Power System in JAXA", the proceedings of the 9th aerospace division international conference on Engineering, Construction and Operation in Challenging Environment (Earth&Space 2004), March 2004, Huston
- [8]Ueno, H., Oda, "Strategy and Ground Experiments on Space Flexible Structure Tracking by Multiple Robots on Vibrating Bases", the proceedings of the RoManSy 2004, June 2004, Montreal