System Analyses and Feasibility Studies for Hyper-OSV (Orbital Servicing Vehicle)

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Abstract
To realize practical orbital servicing missions in 21st century, we have developed the new system concept for the orbital servicing vehicle named Hyper-OSV (Orbital Servicing Vehicle), which has higher speed manipulation capability and larger operation area than OSVs that were proposed in 1990’s. The main feature of Hyper-OSV (HOSV) is the separation of the operation function and the long-term in-orbit surviving functions such as a solar power paddle and a large communication antenna. This releases HOSV from the attitude restriction and flexible dynamics and brings a large operation area. The second feature of HOSV is the reconfigurable function which arrows HOSV to apply various orbital servicing missions. The third feature is that HOSV is designed to be compact and high performance by using advanced electronics. This paper presents the system concept, system design results and feasibility studies of HOSV.

1 Introduction
Recently the construction of the International Space Station (ISS) has begun and the Space Shuttle Remote Manipulator System (SRMS) and the Space Station Remote Manipulator System (SSRMS) are used for the construction. These manipulators are operated by onboard crews and accomplish the tasks that cannot be done by human hands, such as the transportation of large and heavy objects. These manipulators are very useful for these kinds of tasks and very practical because man is in the control loop. However, in the 21st century when more of a variety of space activities on orbit will be realized, it will be necessary to execute a large amount of orbital tasks effectively and there will be orbital tasks in the region where astronauts cannot access easily. In such situation, man should play a role of supervisor for the tasks and a robotic space vehicle should execute the tasks autonomously under the supervision of man. National Space Development Agency of Japan (NASDA) has been doing the research on space robotics [1] to develop a practical and effective orbital servicing vehicle that can fulfill various orbital service missions autonomously [2]. Hyper-OSV (HOSV) is a new OSV concept from our research. We have designed the basic system of HOSV and have been doing feasibility studies of the design. This paper presents the system concept of HOSV, describes the system design results and shows some feasibility studies for HOSV.

2 Analyses for Orbital Servicing Missions
Before the design of a practical orbital servicing vehicle for 2010’s, we analyzed the situation around orbital servicing missions and studied the latest technologies that can be utilized for the new OSV design. In the 1990’s, some orbital servicing vehicles, for example OMV, FTS, OSV [3], were studied and designed. Figure 1 shows the one of the OSV concepts in the 1990’s. However these OSV concepts were canceled at last. The problems for the concepts are summarized as follows:

1. There is no adequate mission to use a OSV.
2. Operation capability is low:
   - Manipulation has to be done slowly due to the flexibility of a solar paddle and communication antenna.
   - Operation area is restricted due to the large body.
   - Attitude is constrained due to the antenna pointing for a data relay satellite.
3. System is complex and its development cost is high.
4. Missions that OSV can cope with are limited.

Figure 1: Outline of OSV [3]
The OSVs planned in the 1990’s would be not sufficiently practical due to the limitation of technology and would be too early to be planned. However, considering the technological progress during these 10 years and the present situation around the orbital servicing, we expect that a practical orbital servicing vehicle can be realized. The situations are summarized as follows:

1. Basic set of the infrastructures on orbit is realized (Space Station, H-IIA rocket, H-IIA Orbital Transfer Vehicle (HTV), Space Shuttle).
2. Success of the rendezvous and docking experiments and the robot experiments on ETS-VII.
3. Progress in electronics (High speed MPU, Large scale ASIC, Network technology, etc.)
4. Progress in software Technology (Parallel computing, Object oriented programming, Information technology, Simulation technology, etc.)

From (1) and (2), the appearance of a practical orbital servicing mission is expected. By using technologies from (3), (4) and (5), we have possibilities to realize a practical orbital servicing vehicle.

Due to the restriction of pages, only some examples of orbital servicing missions in the future are shown in this paper. Figures from 2 to 9 show the prospective missions from our study. The missions shown in the figures from 2 to 7 are expected to be realized within 15 years and those shown in the figures 8 and 9 are expected within 30 years.

Figure 2: EVA support and construction
Figure 3: IVA support
Figure 4: Inspection and maintenance around ISS
Figure 5: Satellite rescue for re-orbiting
Figure 6: Servicing for unmanned platforms
Figure 7: Servicing for unmanned spacecrafts
Figure 8: Construction of large scale structures
Figure 9: Removal of uncontrolled satellites
3 System concept of Hyper-OSV

As the practical and effective orbital servicing vehicle that can carry out various orbital service missions autonomously, we have developed a new OSV concept, Hyper-OSV (HOSV). HOSV can change its configuration according to an executing task. Figure 10 shows the representative operation modes of HOSV. The main characteristics of HOSV are described as follows:

(1) Separation of the operation function and long-term in-orbit surviving functions

In the OSV concepts of the 1990’s, the OSV is large and complex system with a solar paddle and an antenna for intersatellite communication. Thus the OSV has some defects described in chapter 2. To overcome the defects, in the HOSV concept the operation function (HOSV) are separated from the long-term in-orbit surviving functions (mother ship) such as power generation and intersatellite communication and the mother ship supports HOSV for long-term operations. By this separation, HOSV can obtain higher speed manipulation capability and larger operation area than previous concepts of OSV. In addition, the development of HOSV system becomes simple, because HOSV can be designed as a free flying robot and the mother ship can be designed as an ordinary satellite with docking mechanism for HOSV.

(2) Reconfigurable System

HOSV has reconfigurable function that enables HOSV to cope with various missions. To realize this function, HOSV is divided into subsystem modules that are capsulized each other and modules are connected by serial data buses. In other words, the interference between subsystem modules is isolated and the communication between modules is only through serial data buses with dedicated protocol. Thus HOSV can change its configuration easily according to an executing task and can cope with various orbital servicing missions. Furthermore, since each subsystem is modularized and capsulized, we can have clear vision on the development and we can add, change and upgrade the subsystem afterward.

Figure10: Operation Modes of HOSV
(3) Cooperative operation by multi robots
In the conventional OSV concepts, since one versatile OSV executes everything in orbital servicing mission, the OSV becomes very large and complex, which leads to large cost and low reliability. In the HOSV concept, HOSV is designed to be simple; for example, HOSV don’t have the long-term operation functions and is designed as a single system. For orbital servicing missions requiring high reliability, two or more HOSVs are installed to the system. For complex tasks such as plural manipulation, two or more HOSVs execute the task cooperatively. Thus HOSV concept realizes high reliability and large flexibility at system level.

(4) Mobility by walking and free-flying
HOSV has the mobility by walking on large-scale structures such as the International Space Station. Moreover, in order to transport between two separated spacecrafts and to do the inspection from proximity zone, HOSV can fly by equipped with the navigation module and propulsion module. The mobility enlarges the operation area and expands the area of executable orbital servicing missions. We expect that HOSV can cope with orbital servicing missions considered in chapter 2.

4 System Design of Hyper-OSV
To realize the HOSV concept described in chapter 3, the latest electronics (High speed MPU, Large scale ASIC, Network technology, etc.) and software technology (Parallel computing, Object oriented programming, Information technology, Simulation technology, etc.) has been used for the system design. Although we have been designing the basic system of HOSV and have been doing its feasibility study, the system design at present is shown as follows.

The main characteristics of HOSV are shown in Table 1 and the shape of HOSV is shown in Figure 11. The manipulator is symmetric and has 7 degrees-of-freedom (DOF). The end-effectors are attached at the both ends of the arm. Inertial Measurement Unit (IMU), Global Positioning System (GPS) receiver and camera image are integrated for the navigation. Reaction control system (RCS) is used for both the position control and attitude control. As for the attitude control, the non-holonomic motion controlled by manipulator can be utilized because the ratio of weight of the manipulator to that of the body is larger than the conventional OSV concepts. For the communication, HOSV has only proximity communication system to the mother ship and the data link between HOSV and the ground control center is relayed by the mother ship. The electric power is supplied from the battery that is charged when HOSV is connected to the mother ship. For the propulsion

![Diagram of HOSV System](image-url)
system, cold gas jets are expected to use and the propellant is refueled from the mother ship.

To be applicable for various orbital servicing missions, HOSV uses reconfigurable system. Figure 12 shows one of proposing HOSV reconfigurable systems. The system is the distributed control system that consists of capsulized subsystems and the subsystems are connected by high-speed serial data buses. Using this reconfigurable system, HOSV changes the configuration of subsystems according to an executing task. For example, when HOSV is utilized only as a manipulator on a satellite, only the manipulator module is used. When HOSV is utilized for the walking and operating task on large-scale structure, the manipulator, battery and processing module are used. For the inspection from proximity zone, the navigation, propulsion, communication and processing module are used. When HOSV is utilized for the flying and operating task, all modules shown in Figure 12 are used.

| Main Function | - Reconfigurable function  
- Manipulation function  
- Walking function  
- Free-flying function  
- Inspection function  
- Object transporting function  
- Target capturing function |
|----------------|---------------------------------------------------------------------|
| Manipulator    | - Symmetric 7 DOF manipulator  
- End-effectors are attached at the both ends of arm. |
| Navigation     | - IMU-GPS integrated navigation  
- IMU-image integrated navigation |
| Attitude and position control | - Position control by gas jet thrusters  
- Attitude control by gas jet thrusters  
- Attitude control by using non-holonomic motion of manipulator [5] |
| Communication  | - Proximity communication (CDMA)  
- Data transfer to the Earth is via mother ship. |
| Power supply   | Battery (charged by mother ship) |
| Propulsion     | Cold gas jet (refueled by mother ship) |
| Shape          | $180 \times 50 \times 50$ (cm) (see figure11) |
| Weight         | About 50kg |

### Table 1: Main characteristics of Hyper-OSV

5 Technologies used for HOSV system

In this chapter, the technologies used for HOSV are described. The feasibility and specification of the technologies have been examined through the design studies and ground experiments.

(1) Reconfigurable network system

To be applicable for various orbital servicing missions, HOSV utilizes the reconfigurable network system. The system consists of subsystem modules which are capsulized each other and the modules are connected by serial data buses. The main characteristics of the reconfigurable network system are shown below:

- System consists of subsystem modules that are divided in consideration of the system reconfiguration.
- Subsystem modules are capsulized to get rid of the interference from/to other modules.
- Subsystem modules are connected by serial data buses.
- Each subsystem module has the processor element (PE) which takes charge of the system management inside the subsystem and the interface management to other subsystems.
- System reconfiguration can be done automatically at a connection and separation or when a fault is detected.

(2) Paralleled and distributed network computer

For the reconfigurable network system, it is inevitable that many processors are distributed and it is required that those processors are executing tasks cooperatively by communicating through serial data buses. In addition, many levels of task are mixed in the system; there are real-time control tasks that require high reliability and high availability, information processing tasks that require very large processing power, and system management tasks that don’t require being processed in real-time. Thus it is necessary to develop a smart paralleled and distributed network computer system that enables us to develop the reconfigurable network system with clear vision and minimized error.

- The computer system consists of loosely coupled multi-processors that are connected by serial data buses.
- The computer system has system reconfigurable capability.
- The computer system is a scalable system that can increase or decrease the number of processor easily.
- The computer system juggles the high speed processing and the real-time fault tolerance effectively using the task-level parallel processing.

To evaluate its feasibility, we have been doing paralleled and distributed computing experiments using the BBM of MDS-1 PCS [6] which is the prototype of the space born parallel computer system and will be tested on-orbit on MDS-1. Figure 13 shows the BBM of MDS-1 PCS.

(3) Onboard vision / information processing

As missions become advanced and space vehicles become complex, it becomes severe to operate space vehicles from ground and it will be necessary for space vehicles to conduct mission autonomously. One of the key technologies to realize autonomous space vehicle is
onboard information processing which requires large computing power. Especially, onboard vision is important for its rich information in image data. We have been studying the following onboard information processing functions:

(a) Robust vision integrating multi-camera or camera and laser.
(b) Shape recognition and position/velocity estimation by using pattern matching
(c) Motion estimation of Target
(d) Obstruction detection / Onboard surveillance

Figure 14 shows one of examples from our study of onboard surveillance [7]. The collision between a manipulator and an obstacle can be detected by the differential short-term FFT processing of joint torque.

(4) Compact smart end-effector and joint

For HOSV to accomplish a task practically, the compact smart joint having torque measurement capability and the smart end-effector including operation tools for various tasks are essential. As the compact smart joint has a torque sensor in each joint, it is effective for keeping the overall rigidity of a manipulator high and for keeping the overall length short. The joint is also effective for the shock absorbing control to prevent excessive joint torque at capturing. To be versatile for various manipulation tasks, the smart end-effector uses operation tools that are specially designed for specific tasks. As for construction tasks, we have been studying not only the end-effector but also the work site to optimize the overall efficiency for the construction [8]. In the study, communication lines and power lines are attached to assembly components.

(5) Software development and verification system for paralleled and distributed system

As space vehicles become advanced, the degree of dependence on software becomes higher and the scale of onboard software becomes larger. At the same time, since the progress in electronics brings the speeding up of MPU and the scaling up of memory volume, it is not necessary for onboard software to optimize program code and memory allocation severely, which were critical for past onboard software. In such situation, even if the computation power and amount of memory are wasted, we think it would be better to develop onboard software using the object oriented programming which is superior in maintenance and can cope with the correction and extension of specifications easily. In addition, to deal with paralleled and distributed system, onboard software should be built with distributed objects. We have begun the study for the software development and verification system for the distributed onboard software.

6 Feasibility Studies for HOSV

(1) Paralleled and Distributed Control Experiment

The prototype of reconfigurable network control system with distributed processor elements connected by high speed serial data bus was manufactured in trial. The network system has been applied to the control system of the 2-dimensional prototype HOSV manipulator so that we can examine the feasibility and performance of the system through the ground experiment using the real hardware and control software. Figure 15 shows the ground experiment system. Figure 16 shows the example of the real-time task reconfigure experiment. Initially each of the processor elements (PEs) controls its own devices such as joints and camera (Task 1a, Task 2b, Task 3c) and PEs, PEb and PEc calculate also other two joint control tasks (See Figure 16a). For example, Task 1a, Task 1b and Task 1c are same tasks calculated by different PEs respectively. If a single event upset (SEU) occurs in PEb, Task 2b becomes erroneous and the comparison tasks in PEs, PEd and PEc reject the Task 2b results and send the message of the inconsistency to PEb. If the permanent error occurs in PEb, the network control system isolates PEb from the system and other controller such as PEd takes over the joint B control from PEb (See Figure 16b).
(2) Trial manufacture for embedded robot controller

Since HOSV uses a distributed network system, joint controllers are embedded inside the joints. To examine the joint size, we tried to manufacture the small embedded joint controller in trial. The left hand-side of Figure 17 is original joint controller of the 2-dimensional prototype HOSV manipulator. And the right hand-side of Figure 17 is the trial sample of the joint controller (Micro Card) which has same functions and performances as the original one. The trial sample uses Multi-Chip Module (MCM) technique and three dimensional packaging technique to reduce its size. We also examine to use large scale ASIC and Intellectual Property (IP) technology to realize high performance embedded robot controller for next step.

![Figure 17: MCM technique for small joint controller](image)

(3) Trial manufacture for smart end-effector

To examine the design and specification of the smart end-effector for HOSV, we manufactured the prototype model of the smart end-effector in trial. Figure 18 shows the photograph of the end-effector. The end-effector has the grasping function for the handrail and micro-fixture of the International Space Station and can grasp the specialized fixture for the information structures which are assembly components having built-in communication lines and power lines [9]. The end-effector also has socket wrench, CCD cameras, laser pointers and diffused lights.

![Figure 18: Photograph of the smart end-effector](image)

(4) Capturing simulation by free-flying manipulator

The strategy of capturing non-cooperative target by free-flying manipulator such as HOSV has been studied. The strategy of capturing guidance are summarized as follows:

(i) Approach from proximity zone by free flying.
(Execute mid-course maneuvers if necessary)

(ii) Change the attitude so that the body pitch plane coincides with the plane including the grasping point and the velocity vector, which is capturing attitude.

(iii) Control the position of the end-effector by capturing guidance (in-plane guidance and out-plane guidance) so that the end-effector coincides with the grasping point

(iv) Do the grasping guidance to secure the grasping condition until the grasping has completed.

(v) Do the absorbing control to reduce joint load.

(vi) Control the manipulator to stop the relative body motion between the manipulator and the target.
(5) Simulation on attitude control using manipulator

Since the weight ratio of the manipulator to the body in HOSV is larger than conventional OSVs, the attitude control using the non-holonomic motion becomes realistic. The example from our study [5] is shown in Figure 19.

![Figure 19: Attitude change by non-holonomic motion](image)

6 Conclusion

To realize practical orbital servicing missions in 21st century, we have developed the new system concept for the orbital servicing vehicle named Hyper-OSV (HOSV) and have been doing the system design for HOSV adopting the latest electronics and software technology.

In addition to continuing the system design, we have been doing the feasibility study and manufacturing critical technologies for trail. Through the step-by-step ground and in-orbit experiments, we will realize Hyper-OSV for various orbital servicing missions in the 2010’s.

References