THE TECSAS MISSION FROM A CANADIAN PERSPECTIVE

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ABSTRACT

Over the last two decades, the international space community has been discussing the merits of on-orbit servicing (OOS) of satellites. Because of the high cost and risk associated with the establishment of an on-orbit servicing infrastructure, OOS is not yet commonplace. The streamlining of operations is of vital importance to the economic viability of OOS. One of the technologies that will undoubtedly contribute greatly to the reduction of operations costs is on-board autonomy. The Canadian Space Agency is participating to a DLR-led mission called TECSAS whose objective is to demonstrate technologies that are key to the viability of OOS. This paper describes the objectives of the TECSAS mission from a Canadian perspective. Typical operations found in on-orbit servicing missions are described and a comparison of the main missions related to OOS where these technologies were or will be demonstrated is presented.

1. INTRODUCTION

Over the last two decades, the international space community has been discussing the merits of on-orbit servicing (OOS) of satellites. Because of the high cost and risk associated with the establishment of an on-orbit servicing infrastructure, OOS is not yet commonplace. It has only been used for the maintenance of extremely expensive space infrastructure such as the Hubble Space Telescope and the International Space Station using robots such as the Canadarm and Canadarm2. Less expensive satellites or expensive spacecrafts in higher orbits are still generally discarded when encountering major malfunctions or simply running out of fuel.

On-orbit servicing has recently received renewed attention with current or planned demonstration missions such as Orbital Express[1], DART[2], XSS-11[3][4], TECSAS[5] and the possible robotic servicing/decomissioning of Hubble[6]. These missions are respectively funded by the Defense Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration (NASA), the United State Air Force (USAF), the German Space Center (DLR), and NASA. In addition, there are a few studies and development work on servicing commercial satellites.

The TEChnology SAtellites for demonstration and verification of Space systems (TECSAS) is a mission led by the German Space organization (DLR) with Canadian participation. The main objective of the Canadian Space Agency (CSA) with this mission is to provide flight heritage to the Canadian technologies necessary to perform unmanned on-orbit assembly and servicing tasks. TECSAS will consist of a servicer satellite equipped with a robotic arm, as shown in Figure 1, and a client micro satellite to be captured and serviced. CSA will provide the client satellite (QuickSat), which will be equipped with the TECSAS grabbing handle. The proposed concept implies minimum accommodation (structural and attitude control) from the client satellite to support the rendezvous and on-orbit maneuvers to emulate real-life cases. On the other end, the servicer satellite will carry the advanced technologies to be demonstrated for the success of the mission, including a manipulator subsystem and a vision subsystem. Both the client and servicer satellites will be put on their operational orbits from a common launcher. Various Canadian contributions are currently under consideration and include, in addition to the client micro-satellite, flight software for autonomous operations, active vision sensor, onboard pose-estimation algorithms, and the avionics for these algorithms. DLR is also considering the procurement of an advanced end-effector based on SARAH[7].

After the on-orbit delivery and checkout of the satellites, the experimental part of the mission will be initiated and controlled from ground. It will comprise several phases demonstrating the following features:

- Far rendezvous
- Close approach
- Inspection fly around
- Capture of a non-cooperative and cooperative client
- Stabilization and identification of the behavior of the coupled satellites
- Flight maneuvers/orbital changes with the coupled satellites

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- Manipulation on the captured client (OOS representative task such as delivery and installation of a GPS receiver)
- Attitude changes by manipulator motions
- Decoupling of servicer and client satellites
- Formation flight (controlled relative distance, orientation, and velocity)

Fig. 1. TECSAS Servicer Satellite.

For the CSA, TECSAS will serve as a testbed to demonstrate autonomous operations to provide flight heritage to many technologies that were developed for ground control of space-based robots. The lifetime requirement for TECSAS is 3-4 months. After completion of the experimental portion of the program, the Canadian QuickSat satellite will stay on orbit and can be used for further tasks/experiments until its End Of Life (EOL).

This paper describes the objectives of the TECSAS mission from a Canadian perspective. In Section 2, typical operations found in on-orbit servicing missions are described. A comparison of the main missions related to OOS where these technologies were or will be demonstrated is presented in Section 3.

2. ON-ORBIT SERVICING CONCEPT OF OPERATION

Operations in a on-orbit servicing mission generally fall in two categories: vehicular operations such as rendezvous and docking and robotic operations such as capture and berthing.

In the context of TECSAS, DLR and CSA intend to approach the same mission from two drastically different perspectives. DLR's goal is mainly to investigate the use of telepresence, teleoperation and autonomous operations with a ground link for on-orbit servicing whereas CSA intends to concentrate on on-board autonomous operations. Regardless of the approach selected, the concept of operation remains the same in terms of the phasing and description of the mission sequence.

The following sections describe some of the critical phases of a typical on-orbit servicing mission.

2.1 Long-Range Rendezvous

The servicer satellite has completed its orbit phasing and entered into the same orbit or a drift orbit (a slightly lower orbit) of the client satellite with a distance from 5 km to 300 m[8].

The servicer satellite is still controlled with absolute navigation using GPS and some help of relative navigation using radar sensors (and perhaps other sensors such as lidar). The attitude match between the two satellites in this phase is not so important. Other than reducing the distance, actions in this phase also include acquiring and updating the orbiting and attitude knowledge of the client spacecraft; synchronizing the mission timeline; and achieving the necessary position, velocity, and angular rate of the servicer satellite with respect to the client spacecraft for the subsequent close-range rendezvous and docking/capturing.

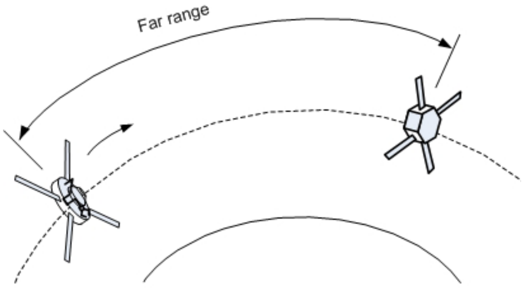

Fig. 2. Long Range Rendezvous.

This operation is done by the servicer only, which is to be guided and controlled by the Russian Mission Control Center (MCC) with the orbital data about the Canadian satellite provided by the Canadian MCC. Since the timelines associated with this part of the mission are long compared to the communication delays, ground operator can be actively involved in that part of the operation. Trajectory correction maneuvers can be pre-computed on the ground and autonomously executed on-board with the ground MCC monitoring.

The client satellite and the robotic system are not actively involved in this operation.

2.2 Short-range rendezvous

The distance between the servicer and the client satellite is from 300 meters to a close distance (several meters) ready for a subsequent docking or robotic capturing operation. The operation has to be controlled by relative navigation technologies by directly sensing the relative position, attitude, and velocities of the client satellite. The servicer satellite has to not only reduce the distance but also the relative attitude as well as the relative velocity and angular rate between the two satellites. The required accuracy in position, orientation, and linear and angular rates may have to be in the order of 0.01m, 1 deg, 0.01m/s and 1 deg/s, respectively, depending on the design of the docking or robotic capture interface.

The operation can be autonomously controlled using the servicer's onboard vision sensors and control system. The ground control system is only responsible for monitoring the operation and providing emergency safety measures. The transition to and from the short-range rendezvous mode under nominal conditions is driven by the relative distance and rates between the two satellites as given by the on-board sensors. It is possible to exit the short-range rendezvous mode upon encountering anomalous conditions such as losing sight of the satellite to be serviced or incorrect approach rates, which would require transition to error-recovery modes.

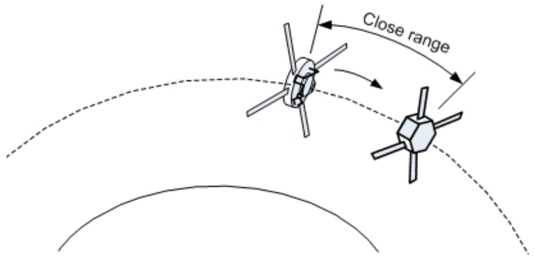

Fig. 3. Short Range Rendezvous.

This operation is accomplished mainly by the servicer satellite. The client satellite is involved only as a target for servicer's sensing system. The robot is not required and thus, it can be powered off and folded in its storage configuration.

2.3 Station keeping

The servicer satellite is in formation flight mode with respect to the client spacecraft in a very close distance such that the client satellite is within the reach of the servicer's robot arm. The relative linear and angular velocities of the servicer satellite with respect to the client satellite must be strictly controlled in order to avoid collision. This phase is highly challenging because of the potential of a collision between the two satellites.

This operation is done mainly by the servicer. It will be used for robotic capture and inspection. It will also be used prior to a docking operation. Because the satellites are in close proximity to each other during this phase, the communication delays and blackouts could result in damage to either spacecraft through a collision or contamination by a plume from the propulsion system. It is therefore imperative to close a control loop on board to maintain a safe distance and to deal with any anomaly conditions such as drift of the satellites or blinding of the vision sensor.

The client satellite is involved in the operation only as a target for servicer's sensing system. The robot is not required for this operation and thus, it can be powered off and folded in its storage configuration.

2.4 Capture

The capture operation is the highest risk phase of the mission since it involves contact between the two spacecrafts and requires a timely cooperation of the control of both satellites.

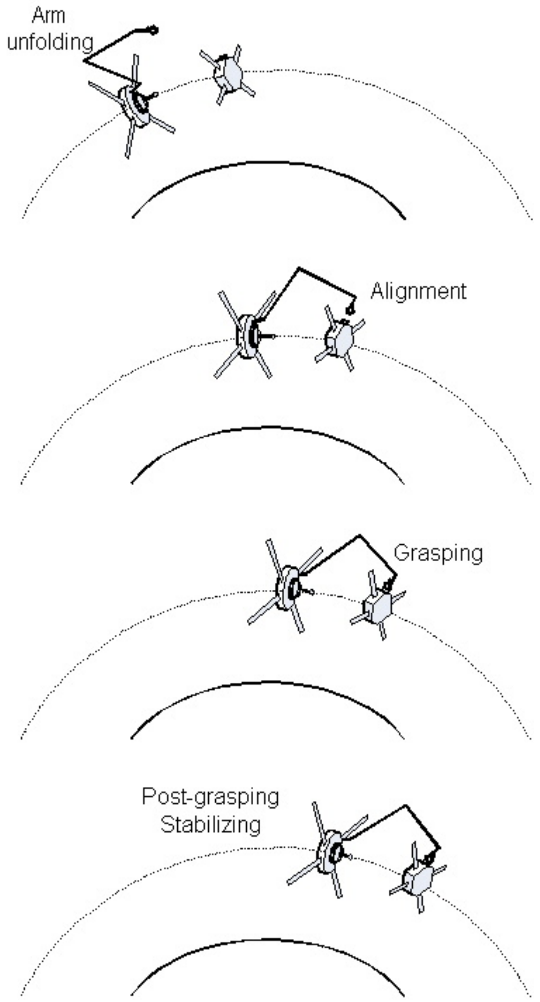

Fig. 4. Capture Sequence.

The servicer's robot approaches the free-floating client satellite and grasps it, as shown in Figure 4. The operation includes the following steps:

1. Power on and unfold the robot
2. The robot arm maneuvers toward the client satellite and aligns its hand with the grasping interface.
3. Upon completing alignment of the robot hand and the grasping interface, the robot arm turns into a limping (joints are passive) mode or force control mode.
4. The servicer may also turns off its Attitude and Orbit Control System (AOCS) so that it becomes free floating.
5. The robot hand then grasps the client spacecraft through the grasping interface.
6. Upon the completion of firm grasping, the robot arm returns to its position control to avoid collision between the servicer and the captured satellite. The servicer should turn back its AOCS for stabilization.

Before capture, the client satellite must be in safe hold mode freely floating on the orbit. Vision servo of the arm will be used for the alignment. After being caught, the motion of the client spacecraft should be completely controlled by the robot arm.

This operation is a robotic operation and thus, the robot plays the essential role. The servicer and client spacecrafts are also involved but they both play a passive role only. The servicer should perform attitude stabilization immediately after the grasping.

Anomalies that can be encountered during this phase include the possibility of the client spacecraft to drift out of the capture envelope of the manipulator (through translation or rotation), blinding of the vision sensor or loss of sight, reduction of the safe distance between the two spacecrafts below an acceptable limit, or failed capture which results in the client satellite to be sent into a tumble.

2.5 Release

This is the reverse operation of robotic capture. It is a robot operation independent from the docking interface. The operation includes the following steps:

1. Open the robot hand from the grasping interface.
2. Move the arm away from the client satellite to avoid collision with the released satellite.

After release, the motion of the client satellite is no longer under the control of the robot. Therefore, if the two satellites are not docked together, the rescuer should then manoeuvre away from the client satellite to avoid collision.

2.6 Docking

The servicer satellite makes a final closing and makes a physical contact with a free-floating client satellite using its momentum (or relative velocity) through a docking interface. As a result, the two satellites are physically rigidly attached together. The operation includes the following necessary steps:

1. Final closing (from station keeping to physical contact)
2. Initial physical contact which may lead to minor bounces.
3. Soft docking in which the two engaging parts of the docking interfaces are mating, which can correct the remaining linear and angular misalignments between the interfaces.
4. Latching (or hooking up) the two interfaces in order to avoid escaping.
5. Rigidization, which makes the two satellite bodies rigidly connected.

During docking, the client satellite must be in the safe-hold mode (SHM) such that the body of the satellite is free-floating in the orbit. This operation requires both the servicer and the client satellites. The servicer satellite plays an active role as opposed to the client satellite which plays a passive role. The robot is not required and thus, it can be powered off and folded in its storage configuration.

2.7 Undocking

Undocking is the reverse operation to the docking, i.e. this operation is used to separate the two satellites. It is successfully completed after the separation of the spacecrafts by a safe distance. The operation requires both the servicer and the client satellites. The servicer satellite plays an active role whereas the client plays a passive role in the safe-hold mode. The robot is not required and thus, it can be powered off and folded away in its storage configuration.

2.7 Berthing

Berthing is a robot-assisted docking operation. This operation includes the following steps:

1. The robot manoeuvres the client satellite toward the docking (or berthing) interface and makes pre-docking alignment.

2. The robot pushes the client satellite against the servicer satellite for soft docking until the two parts of the docking interfaces of the two satellites are latched up.
3. The robot stops pushing and then relaxes itself in the limping or force control mode.
4. The docking mechanism is then activated to rigidize the two satellite bodies into one compound body.

This operation is a robotic operation and thus, the robot plays the essential role. The servicer and client satellites are also involved, but they both play a passive role. The servicer satellite may leave its AOCS on during berthing to compensate some disturbances from the contact in the docking interface or during the motion of the manipulator. If the servicer satellite is in free-floating condition during berthing, it should turn on its AOCS immediately afterwards to stabilize the compound system.

2.8 De-berthing

This is the reverse operation to the berthing operation. The two satellites are detached and moved away from each other by the robot arm. This operation is a robotic operation and thus, the robot plays the essential role. The servicer satellite may or may not be under active AOCS control during the operation but the client satellite must be on safe-hold mode with its AOCS off. The servicer satellite must have its AOCS turned on to stabilize the compound system immediately after a de-berthing.

De-berthing is considered successfully completed only after the two satellites are physically separated to a safe distance by the robotic arm. After de-berthing, the two satellites are still connected by the robot arm.

2.9 ORU Operations

The robot performs ORU operations while the two satellites are rigidly attached together. Potential operations include:

1. Replacing a battery (e.g., a box with peg-in-hole interface).
2. Replacing a fuel tank (e.g., a round-shape container with peg-in-hole interface).
3. Installing a refuelling interface (e.g., a pipe with a peg-in-hole adaptor).
4. Opening and closing a hinged door.
5. Etc.

The standard procedure for a robotic ORU operation is:

1. Power-on and warm-up of the robot hardware and software.
2. Perform a prior-operation checkout.
3. Move the hand toward the ORU.
4. Grasp the ORU and pull it out of its worksite compartment.
5. Put the ORU in a storage place and grasp a new ORU.
6. Insert the new ORU into the worksite compartment.
7. Retract the robot to a safe configuration and put it to a standby or safe-hold mode.

This operation is a robotic operation and thus, the robot plays the essential role. The servicer satellite assists the operation in the sense that it has to use its AOCS to maintain appropriate position and attitude during the operation. The client satellite may or may not be involved depending on whether the ORU is located on it or not.

2.10 Fly Around

The servicer satellite is operated to follow a trajectory or local orbit around the satellite to be serviced. The purpose of this operation is the inspection of the client satellite. This is an expensive operation because the servicer satellite has to continuously fire thrust in order to maintain a local orbit around the client satellite. It is also a risky operation because of the possibility of physical collision between the two spacecrafts. Potential of disturbance or damage by the impingement of the servicer's thrust plume if the two satellites are in close distance is another possible hazard. This operation is performed by the servicer satellite. The client satellite is involved only as a target for the servicer's sensing system. The robot is not required for fly around unless other operations are needed simultaneously during the fly around such as robotic inspection.

3. OOS: PAST, PRESENT AND FUTURE MISSIONS

For many years, robots like the Canadarm and Canadarm2 have been used in space to service expensive space assets[8]. Canada has also developed another robot for the International Space Station (ISS), Dextre, that should be launched in 2007 and will be used to perform maintenance tasks. Other countries are developing robots for the ISS. The European Space Agency (ESA) has developed the European Robotic Arm (ERA)[10] while the Japan has developed the JEMRMS[11].

In order to speed up the acceptance of OOS and decrease operational costs, a few technology demonstrations missions have been or will soon be conducted. Each mission demonstrate some of the typical operations described in Section 2. Japan first conducted the ETS-7 mission in 1998-1999[12]. ETS-7 involved the capture of a target satellite using a chaser satellite equipped with a robotic arm. Both satellites were launched together to minimize risks associated with the rendezvous portion of the mission. The robotic capture was performed while the two satellites were still tied using the latching mechanism, again for reducing the risks[13]. The mission goal was successfully accomplished. The US Defense Advanced Research Project Agency (DARPA) is currently funding the development of the Orbital Express mission to be launched in 2006[1]. This mission intends to prove the feasibility of on-orbit servicing and refueling. The Orbital Express servicing spacecraft ASTRO is also equipped with a robotic arm to perform satellite capture and ORU-exchange operations. In parallel, the US Air Force Research Lab is funding the XSS-11 mission whose objective is to demonstrate key elements of extended proximity operations[3][4]. A mission with similar objectives, DART, was funded by NASA and flew in 2005[2]. The objective was to perform an autonomous rendezvous but unfortunately, the mission failed.

There have been several spacecrafts designed for transporting logistics to the International Space Station such as Russia's Progress[14], Japan's HTV[15], and Europe's ATV[14]. Many key technologies required for OOS were or will be demonstrated with these missions.

At some point, NASA has considered using a robotic mission to rescue the ailing Hubble Space Telescope (HST). Because of the recent Columbia accident, the planned Shuttle mission to service HST has been cancelled and, instead, a rescue mission using robotic arms derived from the ISS’s Dextre was tentatively selected to replace batteries, gyroscopes and possibly a scientific instrument as well. A de-orbiting device would be part of the spacecraft to de-orbit HST at the end of its life[6][16]. However, at the time of writing this paper, this mission has been cancelled.

To define their objectives for the TECSAS demonstration mission, CSA closely studied the missions mentioned above. These missions have occurred, are being conducted or being planned and are relevant for on-orbit servicing. The missions were studied with respect to the typical operations in on-orbit servicing missions, as discussed in Section 2. Three different modes to perform these operations were considered. In the first mode, the Manual Mode, an operator is responsible to conduct the mission by sending elementary commands or using hand controllers. In the second mode, the Semi-Autonomous Mode, an operator is still responsible to perform the operation but part of the operation is automated using scripts that contain the elementary commands or using higher level commands decomposed automatically in elementary commands. Finally, in the third mode, the Autonomous Mode, the operation is performed fully autonomously with minimal number of interventions from the operator. The operator would send only high-level commands like "Capture". An operator can be used to supervised the mission and be ready to send an abort command if needed.

To the best of their knowledge, the authors have listed all relevant missions in Tables 1 and 2 and have identified the operations performed in each mission, differentiating if they were performed manually, semi-autonomously or autonomously. A "C" is used to indicate an operation performed with a cooperative satellite (satellite designed to be serviced and under active attitude control), while "NC" is used for an operation involving a non-cooperative spacecraft (Not designed to be serviced or not stabilized using attitude control). A "-" indicates that the operation was not performed during that particular mission. Finally, the authors used a color scheme to differentiate operations already demonstrated (Green) or planned to be demonstrated in the future (Yellow). The Red color is used to indicate an operation planned to be demonstrated in a particular mission but that was not successful. This notation is summarized in Table 3 for convenience to the reader. It is also important to note that the Hubble repair/De-orbit Mission was not included in Tables 1 and 2 since at the time of writing this paper, it has been cancelled.

All the missions involving a robotic arm are presented in Table 1. The first column in grey indicates technologies planned to be demonstrated during the TECSAS mission while the second column in grey in a summary of all the missions to readily identify is a technology was already tested or planned to be tested in any of the missions. The missions not making use of any robotic arm are presented in Table 2. The last column is a summary of the technology tested in robotic missions, as presented in Table 1. Therefore, looking at the second grey column of Table 2, it is readily possible to identify the technologies covered by any of the OOS missions. From this column, it is apparent that most operations have already being performed for a cooperative spacecraft in Manual or Semi-Autonomous modes. Most of the operations involving a robotic arm were not performed in Autonomous Mode. Moreover, many operations will be demonstrated for non-cooperative spacecrafts, not designed to be serviced but still under active control. However, no operation is planned for the capture of a tumbling satellite, which is an objective of the TECSAS mission.

Table 1. Robotic Missions.

Operations	Mode	TECSAS (2010)	Covered Technology	Canadarm (1981-)	ETS-7 (1998-1999)	Canadarm2 (2001-)	Orbital Express (2006)	Dextre (2007)	ERA (2007)	JEMRMS (2007??)
Far-range rendezvous	M	C	C		C	-	-	-	-	-
	S	C	C	-	C	-	-?	-	-	-
	A	C	C	-	C	-	C?	-	-	-
Close-range rendezvous	M	C	C	-	C	-	-	-	-	-
	S	C	C	-	C	-	-?	-	-	-
	A	C	C	-	C	-	C?	-	-	-
Docking	M	-	C	-	C	-	-	-	-	-
	S	-	C	-	C	-	C	-	-	-
	A	-	-	-	-	-	-	-	-	-
De-docking	M	-	C	-	C	-	-	-	-	-
	S	-	C	-	C	-	C	-	-	-
	A	-	C	-	C	-	-	-	-	-
Robotic capture	M	NC	C	C	-	C	C	-	C?	C?
	S	NC	C	-	-	-	C	-	-	-
	A	NC	-	-	-	-	-	-	-	-
Robotic release	M	NC	C	C	-	C	C	-	C	C
	S	NC	C	-	-	-	C	-	-	-
	A	NC	-	-	-	-	-	-	-	-
Berthing	M	C	C	C	C	C	C	-	C	C
	S	C	C	-	C	-	C	-	-	-
	A	-	-	-	-	-	-	-	-	-
De-berthing	M	C	C	C	C	C	C	-	C	C
	S	C	C	-	C	-	C	-	-	-
	A	-	-	-	-	-	-	-	-	-
ORU operations	M	C	C	-	C	-	C	C	-	C
	S	C	C	-	C	-	C	-	-	-
	A	-	-	-	-	-	-	-	-	-
Orbit transfer of system	M	NC	C	-	-	-	C	-	-	-
	S	NC	C	-	-	-	C?	-	-	-
	A	NC	-	-	-	-	-?	-	-	-
Refuelling / Fluid transfer	M	-	C	-	C	-	C	-	-	-
	S	-	C	-	C	-	C	-	-	-
	A	-	-	-	-	-	-	-	-	-
Fly around	M	C	C	-	-	-	C	-	-	-
	S	C	C	-	-	-	C	-	-	-
	A	C	-	-	-	-	-	-	-	-
Rendezvous (slow tumbling sat.)	M	-	-	-	-	-	-	-	-	-
	S	-	-	-	-	-	-	-	-	-
	A	-	-	-	-	-	-	-	-	-
Docking to slow tumbling sat.	M	-	-	-	-	-	-	-	-	-
	S	-	-	-	-	-	-	-	-	-
	A	-	-	-	-	-	-	-	-	-
Capture of slow tumbling sat.	M	NC	-	-	-	-	-	-	-	-
	S	NC	-	-	-	-	-	-	-	-
	A	NC	-	-	-	-	-	-	-	-

Table 2. Non-Robotic Missions.

Operations	Mode	TECSAS (2010)	Covered Technology	Progress (1978-)	XSS-11 (2005-)	DART (2005)	ATV (2006)	CX-OLEV (2008)	HTV (20XX)	Robotics Missions
Far-range rendezvous	M	C	C NC	C	-	-	C	NC	C	C
	S	C	C	C	-	-	C	-	C	C
	A	C	C NC	C	NC	C	-	-	C	C
Close-range rendezvous	M	C	C NC	C	-	-	C	NC	C	C
	S	C	C	C	-	-	C	-	C	C
	A	C	C NC	C	NC	C	-	-	C	C
Docking	M	-	C NC	C	-	-	C	NC	-	C
	S	-	C	C	-	-	C	-	-	C
	A	-	C	C	-	-	-	-	-	-
De-docking	M	-	C NC	C	-	-	C	NC	-	C
	S	-	C	C	-	-	C	-	-	C
	A	-	C	C	-	-	-	-	-	C
Robotic capture	M	NC	C	-	-	-	-	-	-	C
	S	NC	C	-	-	-	-	-	-	C
	A	NC	-	-	-	-	-	-	-	-
Robotic release	M	NC	C	-	-	-	-	-	-	C
	S	NC	C	-	-	-	-	-	-	C
	A	NC	-	-	-	-	-	-	-	-
Berthing	M	C	C	-	-	-	-	-	-	C
	S	C	C	-	-	-	-	-	-	C
	A	-	-	-	-	-	-	-	-	-
De-berthing	M	C	C	-	-	-	-	-	-	C
	S	C	C	-	-	-	-	-	-	C
	A	-	-	-	-	-	-	-	-	-
ORU operations	M	C	C	-	-	-	-	-	-	C
	S	C	C	-	-	-	-	-	-	C
	A	-	-	-	-	-	-	-	-	-
Orbit transfer of system	M	NC	NC	-	-	-	-	-	-	C
	S	NC	NC	-	-	-	-	-	-	C
	A	NC	-	-	-	-	-	-	-	-
Refuelling / Fluid transfer	M	-	C	-	-	-	-	-	-	C
	S	-	C	-	-	-	-	-	-	C
	A	-	-	-	-	-	-	-	-	-
Fly around	M	C	NC	-	-	-	-	NC	-	C
	S	C	C	-	-	-	-	-	-	C
	A	C	NC	-	NC	C	-	-	-	-
Rendezvous (slow tumbling sat.)	M	-	-	-	-	-	-	-	-	-
	S	-	-	-	-	-	-	-	-	-
	A	-	-	-	-	-	-	-	-	-
Docking to slow tumbling sat.	M	-	-	-	-	-	-	-	-	-
	S	-	-	-	-	-	-	-	-	-
	A	-	-	-	-	-	-	-	-	-
Capture of slow tumbling sat.	M	NC	-	-	-	-	-	-	-	-
	S	NC	-	-	-	-	-	-	-	-
	A	NC	-	-	-	-	-	-	-	-

Table 3. Legends For Tables 2 and 3.

M	Manual Mode
S	Semi-Autonomous Mode
A	Autonomous Mode
-	Not demonstrated
C	Demonstration for a cooperative satellite
NC	Demonstration for a non-cooperative satellite
🟩	Already demonstrated in the past
🟨	Will be demonstrated
🟥	Mission failed

4. CONCLUSION

In this paper, the main missions relevant to the field of on-orbit servicing were described and compared. Operations typical to this kind of mission were identified and described. Manual, semi-autonomous and autonomous modes of operation were considered. Tables were presented to identify the technologies that were or will be demonstrated in these missions. It became apparent that most of them have been or are planned to be tested in manual and semi-autonomous modes for cooperative spacecrafts. This is one of the reasons why the Canadian Space Agency intends to focus on autonomous operations during the TECSAS mission. Capture of tumbling satellites is another aspect important for the Canada in the context of TECSAS.

5. REFERENCES

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