35th Space Symposium, Technical Track, Colorado Springs, Colorado, United States of America
Presented on April 8th, 2019

NASA's Dragonfly Program: Commercialized Robotics - Enabling a New Generation of Evolvable, Resilient Assets in Orbit

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Abstract

Commercialized, affordable robotics for in-space assembly of large platforms and structures are being prepared for flight in 2021. Integrating easily with standard GEO and LEO satellite command and control architectures, these automation systems enable a new operating paradigm for on-orbit assets – one that includes incremental growth, on-demand payload refresh to match user needs, and in-situ warehousing for rapid expansion, augmentation, or dispersion on a timeline independent of launch.

Introduction

The Dragonfly Robotic System, developed first as a DARPA seedling and then maturing through the NASA Tipping Point Program, successfully completed a ground demonstration in late 2017, shown in Figure 1 assembling a Ka band antenna. Critical Design Review occurred in 2018. Ultra-lightweight and affordable, the Dragonfly Robotic System is designed to fit into existing satellite command and data handling (C&DH) subsystems and low rate command/telemetry links for inexpensive integration – it behaves like any other satellite subsystem. The supervised autonomy operating concept facilitates command and control from a standard Mission Operations Center. Current satellite operations personnel can plan and execute robotic operations with only minor additional training. Dragonfly represents the first 'commercialized' robotic system – affordable and accessible to satellite owners without the risk of infrastructure changes.

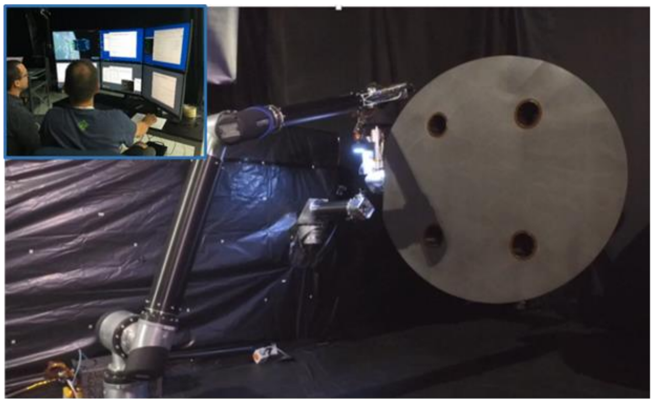

Figure 1: A pilot and co-pilot supervise the automated assembly of a reflector to a GEO Communications Satellite in a 1g demonstration at Maxar's Robotics Lab in Pasadena

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In-space assembly opens a range of new opportunities for satellite architectures and operations. Large structures such as platforms and apertures are no longer confined by the volume limitations of the rocket fairing. Sensitive instruments may be launched in a soft environment, removing the need to survive traditional launch vibration environments, and then installed on orbit and refreshed at a cadence appropriate to the mission need. The in-space logistics paradigm can be transformed to match terrestrial models. In–space storage of ready-to-use components on robotic platforms enables on-demand assembly and dispensing of assets on a timeline that is independent of launch schedule. This operational freedom improves the responsiveness and resilience of services provided by orbiting assets.

Current State of the Art in Earth Orbit

Today's satellites, especially in GEO and beyond, exquisitely optimize mass and capacity to maximize the return on investment and fill the launch vehicle to its limits. They feature a monolithic design that highly integrates sub-systems to the point that 'the payload' is visually and practically indistinguishable from 'the bus'. These vehicles pack as much power and aperture as possible into the limits of the launch vehicle fairing through sometimes extraordinary folding and deployment devices. Figure 2 shows a present day communications satellite in RF testing at Maxar's test range in Palo Alto. It features state of the art solid mm wave antennas for commercial broadband services. Stowed on complex folded booms for launch, these antennas incorporate the largest one-piece reflectors that can squeeze into the launch vehicle fairing alongside the satellite body. A satellite like this may have six to eight complex deployments to achieve this total aperture size. The James Webb Space Telescope takes the folded monolithic architecture to the practical limit with its number of deployments totaling more than a hundred. It is easily the most complicated spacecraft ever attempted in one launch.

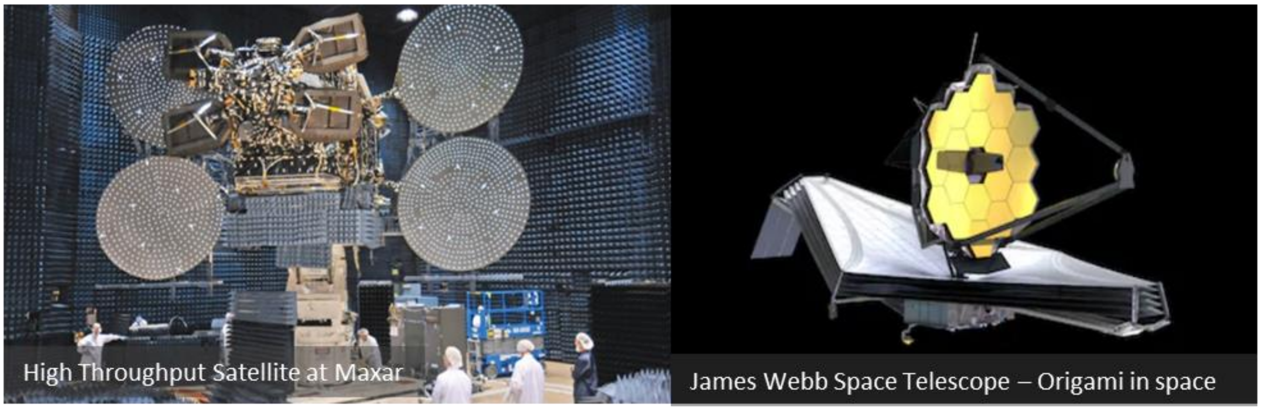

Figure 2: Highly integrated sub-systems and complex deployments attempt to maximize the in-space aperture size and capacity of both commercial communications satellites and National Observatories

As these spacecraft become more folded and more reliant on complicated deployments to function, the Assembly, Integration and Test program becomes long and complex. Because the stowed structures cannot support themselves in gravity when they are deployed, the support equipment required for trial deployments in gravity and in thermal vacuum test chambers becomes as expensive as the flight system.

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And even though deployed structures cannot support themselves in gravity and may be somewhat gossamer when deployed, they must be designed to withstand the vibration and accelerations of launch in their stowed state. This adds mass that is not needed for on-orbit performance.
From a life cycle perspective, the current rigid configuration of a satellite makes repair after a failure or refresh after many years of service impractical. Operators accept reduced or terminal performance after a failure. In addition, operators reposition most GEO communications satellites two or three times in their lives as their intended markets change, their technology becomes obsolete, and their value diminishes. Because they are so highly optimized for their first mission, they are mismatched and unable to adapt to their second and third missions. Often only a fraction of their remaining capacity is effectively utilized.

Government operators have further concerns with fleet management and resilience. Key government assets are very expensive, so procurement occurs in blocks over many years. Unplanned replacement becomes difficult and takes many years. This leads to technology obsolescence and relatively few units in operation both of which increase vulnerability to adversaries. The DoD describes the current situation as: “We’ve gotten very good at building small numbers of extremely exquisite things, very expensive things on very long time schedules. Our savior is going to be the commercial sector. We’re starting to see an influx of commercial technology, but we need more of it, and quick.” - Fred Kennedy, 2017 [1]

What do Satellite Operators want?

The world has changed recently for both commercial and government operators. For commercial operators, change is required to compete with terrestrial communications systems like fiber and to keep pace with rapidly changing markets and technology. The large commercial operators have publically stated that a change is needed to maintain a healthy industry [2]. The next generation of satellites must include the following attributes:

- *Payloads that can respond to dynamic market changes:* the traditional operating plan that procures large, fixed configuration satellites with 15 year lives no longer survives in a world where technology and market demand changes dramatically within five year windows. The need for spacecraft adaptability is sometimes articulated as a need for spacecraft that are reconfigurable enough to support several missions over their lifetimes, or that are economically refreshable in shorter seven year (for example) cycles to remain relevant in the marketplace.

- *Lower investment cost per unit of delivered bandwidth:* This performance metric is often defined as $/Gbps and encapsulates the return on investment (ROI) for operators. Operators demand more throughput for less expensive spacecraft and launches. Increased throughput comes with larger apertures, more power and the ability to better use bandwidth and power by selectively directing it to where it is needed to satisfy demand in real time. But even with these advances, the cost of a mission to GEO is still influenced heavily by launch expenses. Rideshares and ever-larger launch vehicles help reduce this expense but it still drives the ROI equation.

For government operators, rapid availability of capacity where and when it’s needed anywhere in the world is paramount. The ability of adversaries to deny this capacity has changed in recent years, leading to a new set of satellite needs:

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Resilience to uncertain threats: “With regard to military satellites, STRATCOM will advocate for a change away from “exquisite” costly systems that take years to develop in favor of “more resilient, more distributed capabilities.” This is the thinking of the new “space enterprise vision” adopted by the Air force and the National Reconnaissance Office, Hyten said. “That vision is about defending ourselves. In that vision you won’t find any of those big, exquisite, long-term satellites.” [3]. Government operators seek resilience and rapid reconstitution to ensure uninterrupted support of engaged forces. This may come in the form of distributed assets, diverse assets or reconfigurable assets to maintain a widened and uncertain target with uncertain capability.

In-Space Automation – The Agent of Change

To fulfil the emerging needs of commercial and government operators, we need a new operating paradigm in space. The current paradigm favors optimization and its consequence, inflexibility, in part because satellites are out of reach. If satellites are no longer out of reach, they become evolvable, refreshable and dynamic assets that can respond to changing market and mission demands. Similar to terrestrial infrastructures, the new dynamic space infrastructure includes agents of action, hubs and supply chains to sustain the system.

The elements of a dynamic space infrastructure include:
- the ability to ‘do’ things,
- the ability to accept things being done,
- and a supply chain.

In the illustrated example in Figure 3, the ability to do things is executed by the Servicer, which hosts a robotic payload that possesses a wide range of dexterous capabilities, and the Platform, which hosts a robotic helper. Figure 4 illustrates the Restore-L servicer which is one example of a multi-functional agent of change. The platform robotic helper captures and berths the arriving Drone Transporters, and looks after loading, unloading, and stowage of equipment, and assembly, such as building a fleet of small satellites with oversized antennas.

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Figure 4: Restore-L is a good example of a robotically enabled multipurpose (and refuelable) Servicer whose in-orbit transport, assembly and logistics functions are limitless.

Figure 3: One example of a dynamic space ecosystem where servicers, drones and machine tended platforms maintain and sustain a refreshable, distributed capability

The ability to 'accept things being done' is fulfilled by the next generation of satellites and platforms that feature a modular design. Modularity enables payload and equipment exchanges to maintain technical and market relevance and extend profitable/productive life. Large High Throughput Satellites may host their own automated systems to facilitate these exchanges and reconfigurations as needed, while smaller regional or specialty satellites rely on the Servicer for payload replacement. In both cases, the traditional bus element has a long life while the revenue generating payload may be configured for a short life and a low-risk replacement plan.

The final element, the supply chain, consists of launch vehicles, whose capacity is shared among smaller payloads in an attempt to make each mission affordable for all of the stakeholders, and the in-orbit

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transportation agents which include the Servicer and the rather simple-minded Drone Transporters. The Servicer, being a multi-talented vehicle, collects packages delivered by the launcher and delivers them to a receiving satellite or platform. The Servicer has the capability to exchange equipment on stand-alone satellites and platforms, or deliver the equipment to a robotically-enabled Platform or large satellite, where it is installed as a new payload or processed into something new by resident robotics. In contrast, the disposable Drone Transporter contains no real intelligence or capability except for delta-V and the ability to be directed into proximity of the Platform through instructions provided by the Platform via a cross link. This mimics an aircraft on final approach flying under IFR. A propulsive ESPA type vehicle represents a good example of a Drone Transporter. The Platform robotic helper reaches out to capture the arriving Drone Transporter, berths it, and relieves it of its load. Items for disposal are loaded into the Transporter and it is directed to the GEO graveyard orbit or a low altitude LEO orbit for final disposal.

The business and strategic opportunities opened by this new operating paradigm range from self-reconfiguring small-sats to in-orbit warehouses and satellite production facilities. Some exciting very near term possibilities shown in Figures 5 and 6 include:

- *A new business model for commercial communications:* a self-sustaining commercial platform offers prospective clients a leasable geographic space in orbit to position an RF payload. The platform provides power, cooling, pointing, and spectrum rights in exchange for rent. Built as a modular structure, the Platform can place and remove payloads on a month-to-month basis if that serves its clients' needs. The payloads need not be exquisite or long lived, just the minimum to fulfil a pre-set duration to satisfy a business case or mission need. For longer term clients, the payload may be refreshed at a cadence that makes economic sense, which for a 100 to 400 kg revenue generating piece of equipment is much more rapid than for a 3000 to 6000kg wet mass GEO satellite, 100 to 400kg of which is generating revenue at any time. Also, the lower barrier to entry to establish platform based-payload operations in terms of both initial investment and operating overhead, means that the communications market is accessible to more players who fill in the market niches with affordable payloads. Figure 5 shows a concept for a commercial communications platform that hosts a number of tenants.

Figure 5: a Commercial Communications Platform hosts four very large high throughput broadband payloads that share one satellite's worth of 'bus'.

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- *The opportunity for reconfiguration and selectable growth cadence:* for both commercial and government operators, a platform offers a place to grow at a desired rate or store capacity. Stored capacity can be deployed or reconfigured when required. Storing and reconfiguring capacity on orbit separates the on-demand deployment from any launch schedule and maintains an uncertain capability posture. Government and commercial constellation operators may use the platform to build and sustain a fleet of small distributed vehicles that would not be viable for a long life without the resource depot. This mirrors the unmanned underwater vehicle model, where small vessels perform sorties and return to a hub for replenishment and a data dump. This paradigm is further augmented by the Servicer which can deliver small vehicles and sensors to distant places for an expeditionary mission or from Platform to Platform as needed. It is also conceivable that a Platform composed of modules can disperse and reconstitute at another location. But for the present, Figure 6 shows three examples of near-term commercially advantageous in-space assembly. Here, a small robotic system assembles large antennas to fabricate apertures beyond the current state of the art to improve ROI for the operator.

Very near-term commercial missions in GEO that take advantage of in-space assembly will resemble the upper two images in Figure 6. These include assembly of many 3m to 5m antennas whose single piece reflectors are stacked on a satellite's Earth deck for launch, and assembly of a segmented 10m class Ka band reflector suitable for a phased array high throughput broadband satellite. Data throughput and therefore revenue, is directly proportional to aperture size, so it is advantageous to maximize aperture. The current state of the art for solid mm wave antennas is a 3m single-piece unit, four of which can be squeezed into the launch vehicle fairing alongside the spacecraft body. By stacking these single-piece reflectors on the Earth deck for launch, in-space assembly increases the number that fit in the fairing from four to six and increases the maximum diameter from 3m to just under 5m for an aperture increase of 2x to 4x. Segmented solid reflectors, such as our 10m example, promises aperture sizes for mm wave communications that are not even conceivable today.

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Figure 6: Maxar's and NASA's Dragonfly Project, the product of a Public Private Partnership, is an light-weight robotic system that assembles very large solid reflectors for mm wave communications in LEO or GEO. It will be ready to fly in 2021 to demonstrate this capability by assembling a Ka band segmented reflector

Commercialized Robotics – Enabling the New Space Infrastructure

To realize a new dynamic space infrastructure, both the Servicer and Platform must have the ability to:

- Reliably perform operations in space without humans present to get the job done even when things don't work out as imagined
- Reliably perform without a large ground support crew to get the job done affordably

These two operational realities require an architecture that permits ingenuity and resourcefulness when unanticipated situations arise, and automation that, on a day-to-day basis, is trusted and easy to supervise. Building on many years of remote robotic operational experience on the shuttle and ISS, the Dragonfly Robotic System attempts to combine the best of trusted in-space automation with the cognitive advantages of a supervisory ground crew to create an affordable 'expert' robotic system that satisfies these operational realities.

Designed as an ultra-lightweight, affordable robotic system that integrates easily into existing spacecraft C&DH subsystems and control centers, the Dragonfly Robotic System provides state of the art dexterity for all types of in-space assembly tasks and state-of-the-art automation for easy mission planning and execution. The Dragonfly Robotic System began as a DARPA Seedling study in 2015 and has progressed to CDR under the NASA Tipping Point Public Private Partnership Program. Planned to fly in the 2021

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timeframe, the first demonstration of the Dragonfly Robotic System is the assembly of a large Ka/V band segmented reflector similar to the lower image in Figure 6.

Figure 7 shows the key features of the Dragonfly Robotic System. Most notable is the double ended, symmetric, seven degree of freedom design that allows the arm to 'walk' end over end across a large satellite or platform. This mobility keeps the arm small and light while covering a very large workspace.

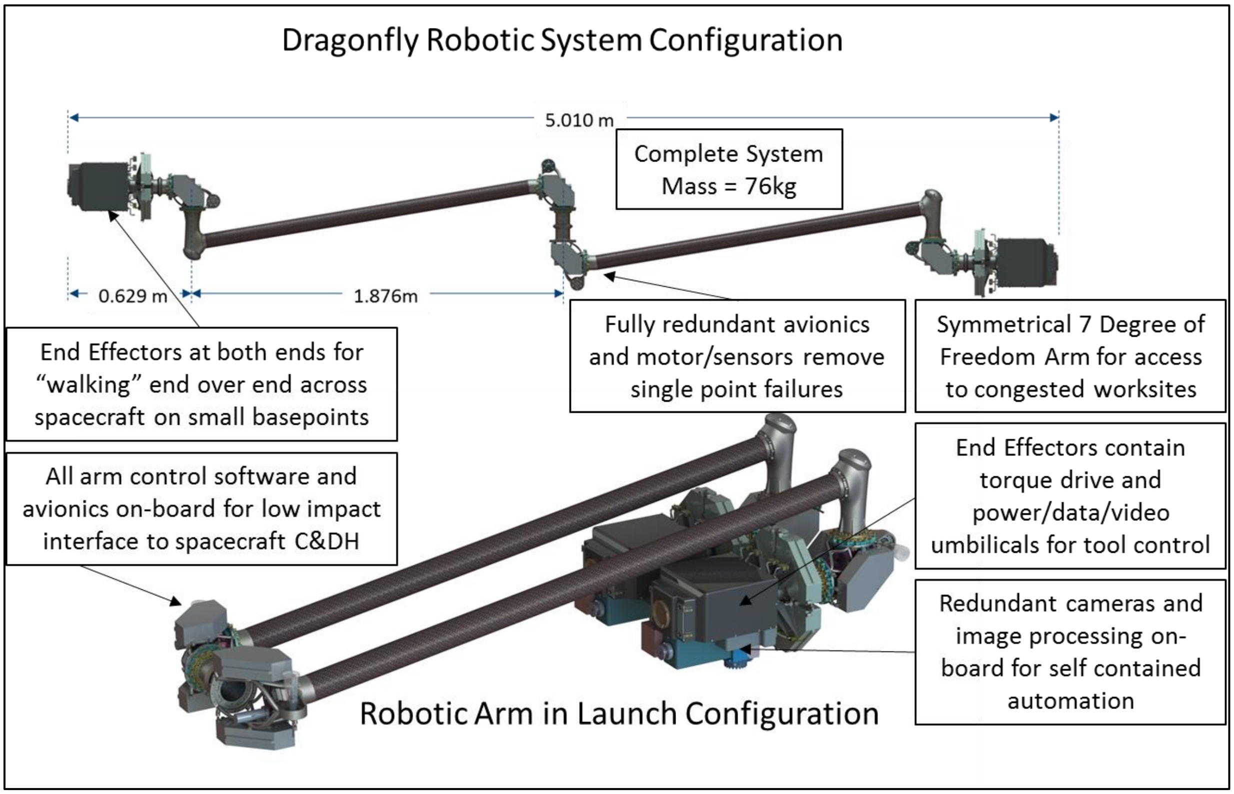

Figure 7: The Dragonfly Robotic System is a self-contained system that walks end over end on small power ports located on a large spacecraft or Platform

Table 1 maps the key features of the arm to objectives and mission functions. Some of the most important features include:

- Double-ended robot for walking end over end to improve functional workspace with a small, lightweight arm
- full on-board redundancy that removes single point failures to support mission-critical ops
- complete on-board avionics, vision and control software for a simple, low rate, asynchronous command and telemetry interface to the spacecraft – same as any other satellite subsystem
- fully automated ops that do not require any changes to existing satellite Mission Control Centers or increased satellite TC&R uplink or downlink bandwidth
- simplified, 3D graphics based mission planning with automatic script generation so that existing satellite mission planners can also fulfil the robotic mission planning role
- available power/data/video at each end effector for added tools, including a tool for visiting vehicle capture and berthing

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Table 1: Dragonfly Robotic System Features and Associated Mission Capability

Arm Feature	Description	Mission Function
Double-ended arm	Each end can act as base or tip with identical performance to 'walk'	A small, lightweight arm can service a large platform or satellite
7 degree of freedom symmetrical configuration with large wrist travel	7 arm joints provides the dexterity of a human arm so that there are many arm shapes available between any two points	Able to operate in highly congested or constrained work spaces, able to reach 'around' obstacles and into confined spaces
Force/Torque sensing and regulation	6 degree of freedom force/torque sensor at each end, torque sensors in each joint drive, and an algorithm to regulate or limit applied or reacted forces to selectable levels	Supports automated assembly using on-board control loops. No need for operator/ground involvement, automatically adapts to misalignments and potential overload or jamming situations before they occur
Handling and control of simple or sophisticated tools	Each end effector contains a torque drive, cameras and power/data/video ports that are accessible for tool use	Such an available resource supports future capability extensions through the use of tools
5m length and medium load carrying capacity	5m tip to tip satisfies most satellite and platform based tasks but length can be varied to match specific mission. Medium load capacity allows the arm to apply forces and react forces as needed	Support a wide range of assembly and disassembly tasks, and with a free flyer capture tool, capture and berth controlled visiting vehicles, such as loaded Drone Transporters up to ~4500kg.
Fully redundant functions	All avionics, cabling, motors and sensors are fully redundant; implemented with two separate functional strings. Hooks for future cross strapping are included.	Removes single point failures to provide failure tolerance for mission critical services
On-board avionics, vision and control software	All arm level and joint level controllers and control software reside on the arm, all cameras and image processing on board, only one prime and one redundant data interface to spacecraft host	Easy to integrate to spacecraft and allows many basepoints for walking arm. Arm behaves like any other spacecraft sub-system, using no more bandwidth than current satellite sub-systems.
Automated operations	All activities are script based, branching on decision points that use real-time status and sensed environmental influences is allowed in the script framework. Real time registration of scripted elements is allowed.	Allows sophisticated robotic operations within a typical satellite Mission Control Center, world-wide network and remote ground station architecture and performance. Removes the need for expert robot operators so that existing satellite mission planners can fulfil role of robot system supervisors during robotic ops
3D graphics based automated mission planning	Robotic planners create operations sequences in a 3D calibrated graphical environment with tools that automatically generate scripts	Reduces special training or skill set within satellite ops team. Allows a small ground support crew during ops and creation of rapid workaround plans.

In order to keep the life cycle cost of the Dragonfly Robotic System low, it is imperative to adapt common robotic operating norms to the existing satellite ground and on-orbit infrastructure and protocols. This sums up to three main design constraints:

- minimize design changes to the satellite
- minimize design changes to the ground segment
- minimize the addition of new skills to the ops team

As described in Table 1, the Dragonfly Robotic System minimizes design changes to existing satellite C&DH and power subsystems by behaving just as other satellite subsystems do. The robotic system accepts 100V or 28V power, standard for almost all satellite buses. The robot communications design

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limits the satellite's C&DH impact to command and telemetry routing, and the robot data volume fits within the existing TC&R (Telemetry, Command and Ranging) communications bandwidth in the satellite bus. The use of the TC&R channels keeps the robot system separate from the satellite payload which mirrors other spacecraft bus subsystems. The Dragonfly telemetry packet can fit within a very small TC&R data stream if required, and can be selectively increased to include more imagery as required by the task at hand, or the available bandwidth. Because robotic operations are scripted, the command data rate is very low, composed of small, asynchronous, discrete commands. This command strategy is tolerant to latency, communications drops and does not stress the existing satellite C&DH sub-system in any way.


Figure 8: The pilot and co-pilot supervise an antenna assembly operation. A combination of telemetry, telemetry driven synthetic displays, and imagery capture from on-orbit cameras provides awareness to the operators. Everything is relaxed and driven with a mouse.

The simple interface to the robotic system also permits the satellite or platform to easily host multiple base operating points for the walking arm. These points consist of small fixtures that include a mechanical interface for load transfer, one set of prime and redundant power lines and one set of prime and redundant data lines.

The satellite Mission Control Center, global network and remote ground station design is also not impacted by the inclusion of the robotic system. As mentioned above, the asynchronous, discrete command strategy is tolerant to ground network and remote ground station latency and does not stress the existing systems in any way. The Robotics Command and Control Console which resides in the satellite Mission Control Center (MCC) connects to the rest of the MCC via the standard LAN so that command and telemetry exchange uses existing protocols and formats.

Finally, the Dragonfly Robotic System operating concept is specifically configured to reduce the skill requirements and workload of the supervising crew. This is done through the scripted mode of operations as described previously, where for everyday and routine ops, three key roles are sufficient to execute safe operations – the Pilot, Co-Pilot and Systems. The supervising pilot monitors current activities at the active end of the robot, provides the authority to proceed commands, and initiates any real-time interruptions that are required. The co-pilot verifies the pilot's actions, provides a second view of current operations via synthetic worksite imagery displays and alternate camera views, and keeps track of the operational sequence. Figure 8 shows the pilot and co-pilot supervising a robotic operation at Maxar's Robotics Lab in Pasadena. Note the lack of joy-sticks – everything is commanded with a computer mouse. The third role, Systems,

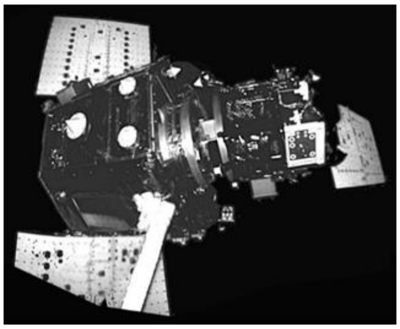
Figure 9: This 'selfie' of the Orbital Express Spacecraft was taken by the robotic arm as it executed a script created by a supervising operator in response to a real-time request

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coordinates with other spacecraft systems and conceives any contingency ops required. This team strategy was used for the 6-month intense robotic operations on the Orbital Express Mission in 2007[4] and is a minor variant of the three key positions in ISS robotic ops. Figure 9 shows a 'selfie' of the Orbital Express Spacecraft. This image is a collage of images taken by the robotic arm as it traversed a scripted path created by the Systems officer in response to a real-time request.

For new and first time operations, a small back room of one or two robotics experts subcontracted from the OEM is recommended. This follows the Medical Device roll-out strategy, where the manufacturer provides expert support during procedures until the resident surgeon is comfortable with the new device. Once the local operators are comfortable, only occasional support is required from the OEM.

To ensure that scripted operations flow smoothly in-space, some important operational features are incorporated in the system. These include:

- updatable planning models using collected in-orbit imagery
- automatic vision-based worksite registration and alignment
- automatic script re-registration
- force/torque sensing and regulation
- situational awareness synthetic views and selectable real-time imagery with frame rate and quality formatted to fit into the regular arm telemetry stream

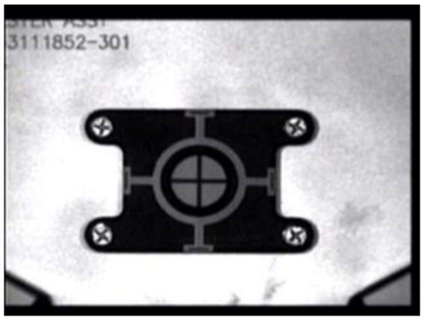

Figure 10: An example of a worksite alignment fiducial used on the International Space Station. The geometry promotes machine vision based pose estimation for accurate alignment corrections.

Because operational scripts are created long before the actual in-space execution, they build on the best 3D models available to planners, typically CAD models. Once in space, the situation may not resemble the CAD model in all respects. For this reason, the Dragonfly operator's console includes a utility that facilitates rapid worksite model adjustments based on collected imagery Once the model is updated to match reality, pre-planned trajectories are validated and adjusted as required.

Next, even though the planning model is as good as it can be, it is not precise. For assembly tasks, the desired alignment tolerances are usually smaller than the accuracy of the model. For this, we include an automatic alignment feature in the robot controller. Here, an image of a nearby fiducial, like the one shown in Figure 10 registers the robot to the actual worksite very precisely. The script accommodates this alignment process by re-registering the remaining segment of the approach trajectory.

Once assembly has commenced and parts come into contact, the robot is equipped to measure the generated forces and torques. The robot has selectable settings that instruct it to limit the maximum applied forces, such as an insertion push force, and the maximum reaction forces, such as the lateral forces generated by misalignments. The robot also has instructions to read, interpret and accommodate misalignment forces in order to automatically improve engagement alignment. This reduces reaction forces for jam-free engagement between the two parts. The algorithms can be set up to avoid jamming before it happens and to limit any force to a safe level. Figure 11 shows Dextre, contributed by the Canadian Space Agency, on the International Space Station automatically inserting a power supply using force/torque accommodation.

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Figure 11: Dextre on the International Space Station automatically inserts a power supply using force/torque accommodation algorithms. The robot is commanded by an operator on the ground using asynchronous, discrete commands that are tolerant to latency and signal drop outs rather than joy-sticks

Finally, while all of these dexterous actions are automatic and do not require operator effort, it is prudent to keep the ground operators aware of the current situation. They can anticipate problems that the robotic control software cannot and can interrupt if things begin to deviate from the planned procedure. They can quickly assess situations and develop workarounds much more efficiently than present-day software. To support this important function, we include arm based camera views of the worksite and telemetry-driven 3D synthetic views. The camera controllers convert large image files into many small data packets so that they fit well within the normal arm telemetry stream. Imagery can be very slow and coarse when the available TC&R downlink is small, but it is still sufficient to provide the awareness that lets the pilot and co-pilot stay on top of the mission. This 'real-time' imagery is combined with the telemetry driven 3D graphical displays that track progress, provide a 'replay' if desired and archive data for later use. The telemetry updates at several hertz which is responsive enough for progress monitoring but can be delayed by transmission and system latency. With planning, the existing commercial ground segment latency is still within the allowable delay for good operator awareness and safe supervised autonomy .

Conclusion

The Dragonfly Robotic System combines the best of heritage Mars lightweight manipulator designs and updated avionics technology with robotic control and operations heritage from the International Space Station and the Orbital Express Mission. A commercialized operating concept provides the first in-space automation product that can be easily adopted by existing satellite operators and their infrastructure. It is our belief that this product will open the opportunity for satellite operators to advantageously change the way business is conducted in space. Improved market responsiveness and improved resilience are just two of the beneficial consequences of including trusted automation in orbiting assets.

Acknowledgements

Maxar thanks and acknowledges the support of the Defense Advanced Research Projects Agency Seedling Program and the NASA Tipping Point Public Private Partnership for enabling this vision to be realized in a timeframe that could establish US National leadership in this new era of space operations. Maxar also acknowledges the Canadian Space Agency's contribution of the robotic system to the International Space Station, and NASA's Space Station Program for creating and maintaining a platform that has enabled the development of deep remote robotic operations experience that can only be realized over the many years of daily operations that the ISS has provided.

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