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ISSUES ASSOCIATED WITH ESTABLISHING CONTROL ZONES FOR INTERNATIONAL SPACE OPERATIONS

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Abstract

Cooperative missions in Earth orbit can be facilitated by developing a strategy to regulate the manner in which vehicles interact in orbit. One means of implementing such a strategy is to utilize a control zones technique that assigns different types of orbital operations to specific regions of space surrounding a vehicle. This paper considers the issues associated with developing a control zones technique to regulate the interactions of spacecraft in proximity to a manned vehicle. It includes discussion of technical and planning issues, flight hardware and software issues, mission management parameters, and other constraints. It addresses manned and unmanned vehicle operations, and manual versus automated flight control. A review of the strategies utilized by the Apollo Soyuz Test Project and the Space Station Freedom Program is also presented.

Introduction

To date, space operations have been conducted in the absence of a large body of international regulations. While some guidelines have been defined in agreements such as the 1967 Outer Space Treaty, each nation has operated according to its own priorities and capabilities. As the number of space-faring nations and orbiting spacecraft increases, it seems desirable to develop an international strategy to coordinate, monitor, and control the interactions of spacecraft in orbit. Successful strategies will facilitate cooperative operations while supporting each nation's goals and objectives in space. The potential benefits of such a strategy include reductions in future program costs and increases in mission success and safety through the standardization of space operations and equipment; increased safety through development of a coordinated collision avoidance strategy for active spacecraft; and the establishment of a basis for legal and economic compensation agreements.

Any traffic management concept should address a number of general requirements. First, the concept should allow for standardized mission planning and operations. To facilitate this, the routine need for long lead time preparation prior to execution of the mission should be avoided. Second, the concept should permit standardized flight and ground crew planning and operations. This standardization will simplify training and day-to-day activity planning. Third, the concept should allow for early definition of requirements for communications, tracking, telemetry, and command and control. Finally, any plan for coordinating space operations should provide for collision avoidance between spacecraft and hold disturbances and contamination from thruster firings to a reasonable level.

There are many ways to meet the requirements outlined above. One means is to utilize a control zones technique that assigns different types of orbital operations to specific regions of space surrounding a vehicle[1]. Such a strategy offers the advantage of clearly delineating the responsibility of both vehicles as a function of their relative positions, velocities, and time. It is unambiguous because these quantities can easily be determined onboard the spacecraft or on the ground using existing technology. While zone-based strategies can be utilized to regulate a wide range of orbital operations, this paper only considers the issues associated with developing a control zones technique to regulate the interactions of spacecraft in proximity to a manned vehicle. However, it should be noted that many of these same issues will apply when expanding the control zones concept to longer ranges and more classes of spacecraft.

This paper outlines a set of items that should be considered when developing international standards for traffic management using a zone-based technique. It then discusses each of these items in terms of the major issues that will influence its standardization. Cost implications are also discussed, where appropriate.

It should be noted that this paper does not attempt to address the full range of policy-related questions, such as defining the legal basis that nations have for establishing some form of authority over a region of outer space. It assumes that such questions will be answered elsewhere. Nor does it seek to sell the worth of a control zones strategy. Rather, it assumes that the international community will recognize the benefits of such a strategy for at least one class of orbital vehicles (e.g., space stations) and develop an appropriate set of international standards.

Definitions

The following terms will be utilized throughout this paper and are collected here to facilitate understanding of the issues and provide easy reference.

- Rendezvous target - the vehicle that one is attempting to rendezvous with.
- Control authority - the authority to make major decisions on the conduct of a mission, such as aborting the mission.
- Flight crew - the personnel onboard the manned base.
- Ground crew - the personnel on the ground who support the premission preparation and real-time execution of the manned base's mission.
- Vehicle classes - vehicles that possess the same basic characteristics and fulfill the same basic mission. For example, the Soviet Shuttle Buran and the American Shuttle Atlantis belong to the same vehicle class; both are manned vehicles that ferry crews and supplies into orbit.
- Teleoperated vehicles - unmanned vehicles that are remotely piloted during all or part of their nominal trajectory. For example, NASA's orbital maneuvering vehicle will utilize a ground-based pilot to perform docking operations with the target spacecraft.
- Autonomous vehicles - unmanned vehicles that execute rendezvous, proximity operations, and docking through the use of automated flight control techniques and do not nominally require a remote pilot.
- Zonal authority - the authority granted to a manned base within a specified region of space by the international community. It includes the rules of operation within such a zone, as developed by the base vehicle's controlling nation, program office, or control center

and agreed to by the international community.

- Control zones - the regions of space in which zonal authority is exercised. For Space Station Freedom, this is called the "command and control zone" (Figure 1).
- Manned base - a manned spacecraft that has been allocated control zones.
- Zonal compliance - meeting the requirements of a given control zone.
- Transient vehicles - those spacecraft that enter a given control zone, but do not nominally plan to interact with the manned base (e.g., operational satellites).
- Mission management parameters - For the purpose of this paper, these are defined as data that enable ground controllers and onboard crewmembers to monitor mission progress and make decisions in real time. Included in these data are the nominal mission plan, preflight determined contingency plans, real-time status of safety critical vehicle systems, vehicle state vector data, etc.
- Interacting vehicle - any spacecraft that enters the manned base's control zone.
- Zone activation period - the period of time when the manned base may exercise its authority over its control zone.

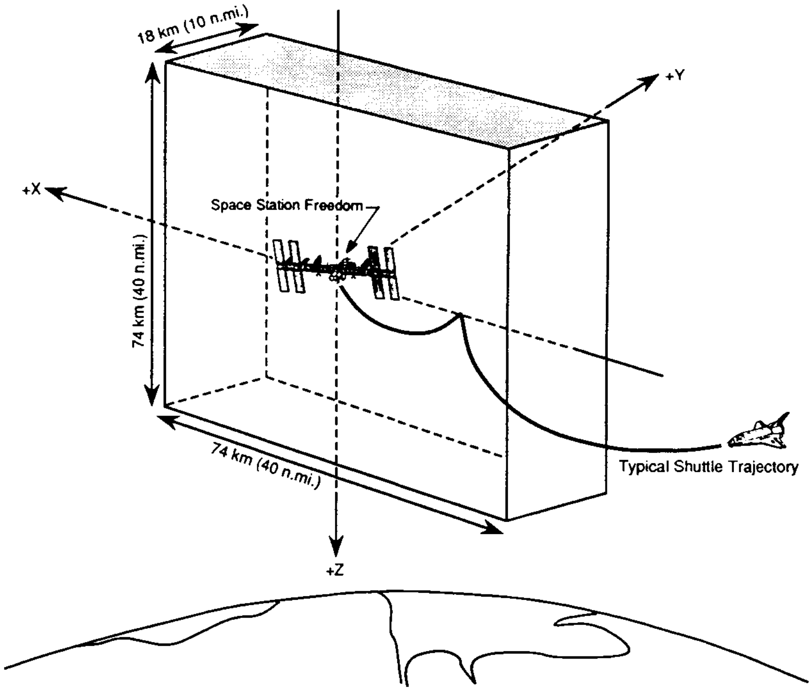

Fig. 1 Space Station Freedom's command and control zone.

- Dynamic control - to actively pilot a vehicle.
- Berthing - the linkup of one orbiting object with another, wherein the closing energy is provided in a closely controlled fashion by an intermediate mechanism attached between the two[2]. This mechanism is typically a remote manipulator, such as the Space Shuttle remote manipulator system.
- Observable parameters - data that can be obtained through observation of the interacting vehicle by active (i.e., radar) means or by passive means (eyeball) from the manned base without the use of telemetry.

Historical Precedents

This section summarizes the traffic management-related elements of Space Station Freedom and the Apollo Soyuz Test Project in order to outline the historical precedents for the remainder of the paper. The references cited can provide more information to the interested reader.

Space Station Freedom

Space Station Freedom plans to implement a limited control zones strategy for regulating its interactions with other spacecraft. This strategy assumes a command and control zone as shown in Figure 1. The regulations for this zone designate the ground as the primary control authority, until the vehicle enters the control zone. Then, Freedom becomes the primary control authority[3]. While the specific regulations vary as a function of vehicle class, Freedom has the authority to "wave off" cooperating manned or unmanned vehicles operating within the control zone[3]. For unmanned vehicles, Freedom will "exercise dynamic control" and have "hazard critical systems monitoring/command capability"[3] while they are inside the control zone. The unmanned vehicle's ground control center will serve as a backup for Freedom's dynamic control and also monitor the full set of systems parameters. In the event of a communications failure between Freedom and the vehicle, control will revert to the ground. Alternatively, when interacting with manned Space Shuttle Orbiters, Freedom will have two-way voice communication[3], but will rely on the ground for trajectory and systems monitoring. It should be noted that regulations have not yet been developed for manned vehicles other than U.S. Orbiters (e.g., Hermes or Buran).

Freedom is implementing the necessary communications capabilities to support these regulations. At the same time, other vehicles such as the Space Shuttle Program is developing the necessary Freedom-compatible interfaces.

Apollo Soyuz Test Project

The Apollo Soyuz Test Project was among the first instances of cooperative international space operations. Its purpose was to dock two manned spacecraft in low Earth orbit: the American Apollo and the Soviet Soyuz. The test project did not utilize a control zones strategy as such. Rather, it relied on a set of mission-unique flight rules that were jointly agreed upon prior to the mission. However, these mission rules[4] had the same effect (i.e., to monitor and control the interactions of two spacecraft in proximity to each other).

Apollo began monitoring the relative trajectories upon sensor acquisition. Soyuz served as the rendezvous target while Apollo performed the actual rendezvous maneuvers. The Apollo and Soyuz ground control centers were the control authorities for most of the mission. However, the spacecraft commanders exercised controlling authority during the docking phase. They also exercised authority if communications were lost with the ground, or in contingency situations that required rapid responses. The ground monitored vehicle health and trajectory, computed the long-range rendezvous maneuvers, and coordinated mission execution. Once within its sensor range, Apollo computed the necessary rendezvous maneuvers (though the ground retained primary control authority). Apollo and Soyuz could communicate between themselves by voice link and thereby exchange relevant data, but neither could monitor the other's telemetry.

Items To Be Considered When Developing International Standards

Development of a zone-based traffic management strategy will require the international community to agree upon a set of standards that reflect a wide range of technical disciplines and issues. Such standards must be specific enough to be useful for near-term missions, but flexible enough to serve as a basis for long-term coordination and cooperation in space. This section outlines eight areas that should be considered in developing these standards.

1. First, the community should determine the classes of spacecraft that should be assigned control zones. For example, will only space stations have them, or will shorter duration orbital missions (e.g., space shuttles) also benefit from having such zones assigned to them?

2. Second, the type of vehicles that must comply with such zones should be defined. For example, must satellites whose orbits occasionally cross a manned base's zone comply with communications requirements for that zone?

3. Third, the size of zones allotted to each class of manned base should be decided. For example, Space Station Freedom currently has a control zone that extends +37 km (20 n.mi.) horizontally and +37 km (20 n.mi.) vertically (Figure 1). This zone is +9 km (5 n.mi.) in the out-of-plane dimension.

4. Next, the community should agree upon the regulations that apply to vehicles operating within a control zone. By analogy, these are similar to laws governing commercial air traffic. They regulate which vehicle is in control at a given time, the approach corridors to be utilized, monitoring requirements, etc.

5. The community should define the parameters that a manned base will monitor within its control zone. For example, will they be limited to trajectory data or will they include safety-critical systems data for the interacting vehicle?

6. The duration of each zone's activation should be determined. For example, should a vehicle's control zone be active continuously, or should it only be active during particular mission phases or operations?

7. The performance parameters necessary to ensure compatibility of communications and telemetry should be considered. These parameters can include the frequency of operation, polarization, spatial coverage modulation and demodulation protocols, and system operational modes.

8. The international community should specify the tracking parameters and

measurement accuracies necessary to assure tracking system compatibility.

While the list just presented is not comprehensive, it is thought to represent the scope of the problem. Accordingly, each item on this list will now be addressed in a separate section where the relevant issues are discussed in detail. Discussion will include its technical and planning aspects, as well as concerns with flight hardware and software, mission management parameters, etc. These issues, in turn, can be utilized to identify follow-on studies that will ultimately result in a set of international standards. Note that a summary of both the items and their related issues is presented in Table 1.

Discussion of the Issues

1. Classes of manned spacecraft to be assigned control zones

One advantage of control zones is that they provide a framework in which to organize and coordinate on-orbit operations between programs and nations. However, it must be noted that joint missions have been conducted successfully in the past without a control zones strategy (e.g., Apollo Soyuz Test Project). In such cases, negotiations are conducted between the nations or parties involved to determine the physical interfaces, flight rules, constraints on mission design, and other details.

Table 1 Summary of standardization items and their related issues

Standardization	Related issues*
1. Classes of manned vehicles to be assigned control zones	• Number of interactions = f(class of manned vehicle) • Vehicle design = f(cost to modify) • Mission design, mission management data = f(standardization)
2. Classes of vehicles that must comply with control zones	• Apply zone to all vehicles = f(cost to implement, workarounds) • Frequency of interaction = f(cost of mission-unique planning) • Controllability = f(manned, unmanned, autonomous) • Hardware & software = f(vehicle design, zonal regulations, zone size) • Planning, mission management data, training = f(interaction, contingency planning, zonal regulations)
3. Size of zone allotted to each manned base	• Safety = f(vehicle class, trajectory, relative velocities, evasive maneuvers) • Base's altitude = f(value of orbit, population) • Hardware & software, planning, mission management data, training = f(zone size, hardware limitations)
4. Regulations that apply within control zones	• Apply same rules to all vehicles = f(standardization, cost to comply) • Apply rules retroactively = f(hardware impacts) • Types of regulations; e.g., dynamic control = f(manned, unmanned, communications time delay, communications link reliability, system reliability, docking/berthing, hardware & software)
5. Parameters to be monitored	• Regulations, zone size, range • Monitor only observable parameters = f(manned, unmanned, base's sensor array) • Monitor telemetry; e.g., safety critical systems data = f(communications link reliability, hardware & software impacts, ground processing time)
6. Duration of each zone's activation	• Impacts of continuous activation • Impacts on manned base
7. Communications and telemetry compatibility	• Standardized parameters • Manned base's antennae coverage = f(zone regulations, range, relative attitude) • Level of conformity = f(technology) • System automation level = f(cost, technology)
8. Tracking compatibility	• Sensor type = f(trajectory, zone regulations) • Standardized parameters = f(trajectory, zone regulations)

* The following notation is utilized to explain the related issues:
- Each issue is shown on the left side of the equation and each factor that influences it is shown on the right side.
- Issue = function of (various factors) = f(factor #1, factor #2, factor #3)

Therefore, the point to be decided is: how many interactions must occur over the program lifetime before the cost of mission-unique efforts exceed the cost of conforming to international standards? One factor is the class of manned vehicle being considered for a control zone. It is possible that cost savings for vehicles with short mission durations (e.g., orbital shuttles) may not match savings for vehicles with longer duration orbital missions (e.g., space stations). Trade studies may show that it is not practical to develop regulations for more than one class of manned base at the present time.

Another area that will influence this decision is vehicle design. It seems reasonable to expect that signatories to an international agreement will incur additional short-term program costs to purchase or develop the flight hardware and software necessary for compliance. For example, hardware items such as sensors are probably required to accomplish any cooperative space activity, and are required regardless of whether or not international standards exist. However, additional costs could occur if the regulations that are eventually developed require sharing of that sensor data between the two vehicles. If the vehicles are already designed or operating, the costs of new designs and retrofitting may be prohibitive. However, it may be possible to design one device that conforms to international standards and procure multiple copies of it. Thus, the nation could realize a long-term savings.

The impact of standards on mission design, mission management parameters, constraint development, etc. should also be considered. Standardization is very desirable in these areas because of the amount of work required to generate mission-unique data products and train ground and flight crews. This process could evolve to a point that a standard set of products is always required to interact with a given vehicle. That would eliminate the need to negotiate new products and data for each rendezvous mission. In a sense, this is similar to air traffic control. A controller in London receives a flight plan with all the necessary information in it before a French airliner reaches his airspace.

Note that the significance of these issues, costs, and savings will vary with the types of regulations that are eventually developed for the zones. For example, if participants agree that direct trajectory monitoring is not necessary, then a radar may no longer be needed onboard the manned base.

2. Classes of vehicles that must comply with control zones

The international community should first consider whether a manned base's control zone should apply to all spacecraft that enter it, or only to those spacecraft that intend to interact with the base. For example, an operational satellite may enter a control zone occasionally, but never plan to interact with the manned base. Establishing zonal compliance for such vehicle classes may prove to be an unreasonable cost impact. This impact is particularly a concern for manned bases operating at high altitudes, such as geosynchronous Earth orbit. Accordingly, the international community must consider the actual motivation for requiring compliance, and determine if any valid workarounds exist. For example, near-term concern for potential collisions with operational satellites might be addressed by arranging for some organization to notify the manned base when a spacecraft is going to enter its vicinity. The manned base could then go to "alert" status for potential collision avoidance maneuvers. Then, over the long-term, the international standards could be expanded to allocate additional zones for unmanned vehicles such as satellites. Manned spacecraft could then be restricted to operate outside of these zones.

Next, consider the vehicles that will interact with the manned base. One means of determining which classes of these vehicles should be subject to compliance is to consider how frequently the interactions are expected to occur. Obviously, the more frequently a spacecraft enters a manned base's control zone, the stronger the case for establishing zonal compliance. Such compliance simplifies interfaces, enables mission standardization, etc., as was discussed in an earlier section. However, this standardization may once again require a trade study to determine how frequently the interactions must occur before the cost of mission-unique development and planning exceeds the cost of standardization.

Another matter that will influence this decision is the controllability of the spacecraft in question. A spacecraft approaching the manned base must provide an adequate margin of safety for the base's crew. The question to be decided is what constitutes an adequate safety margin? Manned vehicles may not be as critical in this regard as other classes of spacecraft because a crewmember is a good monitoring system. He/she can see out the window, adapt to trajectory dispersions, and make rapid decisions during contingencies. Since a crewmember's abilities may provide the necessary safety margin, one could make a case to exempt or limit manned vehicle compliance with such regulations.

The controllability of unmanned vehicles may be less certain. By their nature they may represent an increased threat to a manned base (i.e., there is no one aboard). Teleoperated vehicles present a potential safety hazard during proximity operations and docking because of the communications time delays that slow the pilot's ability to react to dispersions and/or contingency situations. An additional safety concern may occur if the communications link fails during proximity operations. In both of these cases, the incoming vehicle could be relatively uncontrolled and on a collision course with the manned base. Both of these concerns will be discussed at greater length in section 4 of this paper.

Autonomous vehicles may have less controllability concerns than other unmanned vehicles. Once they are tested and certified, concerns about time delays may be reduced because everything is computed and executed onboard. It is still expected that the manned base's crew will want to monitor the incoming vehicle's trajectory and possibly its systems, and precedent exists for such monitoring. For example, Soviet cosmonauts monitor the trajectory of Progress tankers by television during the final phases of their docking operations with the Mir Space Station.

In section 1, it was observed that assigning a control zone to a given manned base might increase its hardware and software requirements. This increase may also be true for the classes of vehicles required to comply with those control zones. The extent of these impacts will be a function of the spacecraft capabilities, the regulations that apply within a control zone, and the size of the zone. However, in general, it can be assumed that spacecraft already planning to interact with the base will experience less impact from compliance than transient vehicles. For example, payloads may already provide safety critical data to the U.S. Space Shuttle, so there may be limited impact if these data must also be provided to a space station. However, transient vehicles may require system changes, with the associated weight, power, and cost penalties, to comply with the zone.

Zonal compliance may also be expected to increase both the amount of planning to be done and the mission management data to be generated. If a vehicle already plans to interact with the manned base, then a significant amount of premission coordination will be conducted regardless of the existence of a control zone. The existence of a zone may require some new data to be generated, but this should be limited because similar types of planning data are probably necessary in either case. However, the manned base may incur additional planning costs if its support personnel are required to generate the plans for interacting vehicle's contingency operations within the control zone. Finally, depending upon the control zone's regulations, training may also be expected to increase. For example, if the manned base's crew is to monitor the interacting vehicle's systems data, then they (and possibly the ground controllers) must be trained to understand it.

These effects on planning and training are magnified if transient vehicles are required to comply with zonal authority. In this case, the additional coordination and regulations may represent a significant planning overhead to these spacecraft, because they may not have planned to generate such mission management parameters.

3. Size of zone allotted to each type of manned base

Safety requirements may be expected to have a significant influence on the size of a manned base's control zone. In short, the zone must be sized to provide adequate time for the flight crew to recognize a problem and respond to it. Some of the many factors that influence this issue are discussed below. Note that in all cases described below, it may be difficult to infer the zone size for an entire class of vehicles from the results derived from one specific example. Therefore, sizing studies should consider several vehicles in the same class when assigning the manned base's zone size.

It has been observed that safety requirements may vary with the class of vehicle interacting with the manned base. Accordingly, vehicle class may be expected to influence zone sizing. For example, it is possible that detailed risk assessments may require monitoring of unmanned vehicles at greater ranges than a manned vehicle, simply because of the controllability concerns discussed earlier. If this proves to be the case, then the zones must be sized to provide adequate sensor and communications coverage for the classes of vehicle in question.

The trajectory followed by the interacting vehicles may also be a factor, depending on the zone regulations that develop. For example, zone regulations may require that the manned base monitor the critical portions of the interacting vehicle's trajectory, such as execution of the intercept maneuver. To do this monitoring, the zone should be sized to include those trajectory phases. This monitoring was one factor that influenced the sizing of Space Station Freedom's command and control zone (i.e., it was sized to allow tracking of the Orbiter for 1/2 orbit prior to the intercept maneuver). Obviously, the trajectory is a function of many things, including trajectory dispersions, crew activity plans, etc. Hence, each of these things will also influence zone sizing.

The relative velocity of the approaching vehicle must be considered. The faster a vehicle approaches the manned base, the larger the zone may need to be in order to allow the same amount of monitoring time. This zone size may be less of a concern for vehicles engaged in rendezvous and docking, as relative velocities are generally well controlled by the trajectory design. However, it may be a serious consideration if the zonal authority extends to transient vehicles such as satellites.

Safety should consider whether or not the manned base is capable of performing evasive maneuvers. The zone should be sized to allow adequate time to react to collision threats. Some of the elements influencing reaction time are the manned base's sensor capabilities and the acceleration capability of the interacting vehicle. A manned base with significant capability to perform evasive maneuvers can reduce the reaction time which might reduce zone sizing. Caution is urged in exercising this means of reducing zone size, however. Cooperative aborts will result in two vehicles maneuvering in close proximity to each other which may raise more safety concerns than it solves; cooperative aborts may be much more complex because the dispersions and failure modes of two vehicles must now be considered. Planning such maneuvers may increase the premission planning, training, and system verification.

Another issue in determining zone size is the operating altitude of the manned base. Currently, large volumes of space exist between various spacecraft in orbit. However, as the on-orbit population increases, the competition for available space can be expected to increase. Such competition is already evident for satellites in geostationary orbit. It therefore seems likely that the international community will wish to limit the size of zones in order to ensure equal access to the orbit resource. Alternatively, such population increases represent increased activity in the vicinity of the manned base, and as such, could be grounds for larger zones, or at least additional zones with different regulations.

While some issues related to hardware, software, planning, and mission management parameters have already been discussed, it is difficult to identify the full range of such issues and to quantify their significance in determining zone sizing. It is probably safe to say that the larger a zone is, the greater its impact on these items. For example, monitoring a large zone may drive additional weight, volume, and power requirements for equipment such as radar aboard the manned base. Large zones may also increase premission planning because more phases of the trajectory must be examined. This increased planning will involve more disciplines to assure zonal compliance. Monitoring more trajectory phases may also require additional mission management parameters to be developed premission and monitored in real time. This additional development will also increase planning costs and require additional training. Alternatively, it may not be possible to increase certain hardware parameters such as power levels. Thus, hardware limitations may feedback into this process and limit zone size and shape.

Finally, proprietary and security concerns may also be expected to influence zone sizing, but they are outside the scope of this paper. For example, it is unknown whether distancing vehicles is an acceptable means of ensuring proprietary and national security.

4. Regulations that apply within control zones

One issue is whether the same regulations should apply to all interacting vehicles, or should they vary by vehicle class. Applying the same set of rules to all interacting vehicles will enhance standardization and may reduce training. However, it may also drive excessive and unnecessary hardware and software development because it seems unlikely that all vehicles will require the same level of monitoring. Thus, standardization in this regard runs the risk of overspecifying the solution at a significant increase in implementation cost.

The community should also consider the worth of retroactively applying the regulations to existing spacecraft or those far along in their design cycle. In some cases there will be only limited conflicts between the regulation and the vehicle's current capability. However, other cases are likely in which the incompatibility and resulting hardware impacts could be more extreme. For example, interfacing to Orbiter avionics in nonstandard ways can be difficult due to space limitations for cabling. Hence, some criteria must be developed to decide when the cost of vehicle modification outweighs the need for compliance. Regulations might be assigned a graduated importance, where those related to safety critical concerns are levied on the existing vehicle and others are addressed by operational workarounds or waivers. However this is resolved, it should be noted that there is at least some precedent for requiring vehicle modifications to meet new safety standards after development is under way. Following the Challenger accident, updated safety requirements were levied on all payloads slated to fly on the Orbiter, regardless of their state of development at the time.

This paper discusses issues rather than specific proposals. Thus, it does not discuss specific regulations. However, there are certain types of regulations that may be common to various zones. Discussion will now address the issues associated with types of regulations that require dynamic control, because they are illustrative of issues that may be encountered when defining the actual regulations and because they are of specific interest to the international community.

The community should consider the necessity for those types of regulations that require dynamic control of specific vehicle classes from a manned base. A regulation of this type might require that the manned base's personnel remotely pilot the interacting vehicle when it is within the control zone. Such regulations may be strongly driven by safety concerns, and are therefore a function of vehicle class, system redundancy, and other factors. There is probably no need or intent in the international community to remotely pilot an interacting manned vehicle. Therefore, consider the issues that influence the applicability of this type regulation to various classes of unmanned vehicles.

One influence could be the existence of a communications time delay between the ground-based pilot and the orbiting spacecraft. This is the case with some teleoperated vehicles, such as the U.S. orbital maneuvering vehicle. Such time delays can make it difficult for the pilot to rapidly respond to changes in relative position and attitude under nominal conditions, much less contingencies such as failed-on thrusters. Thus, teleoperation from the ground could present an increased threat to the manned base and/or a reduced probability of mission success for the vehicle. Lower mission success rates may be unacceptable for operations involving manned vehicles. However, the significance of this issue will also be a function of the minimum translational and rotational rates that the vehicle can consistently maintain during those operations. For example, small minimum rates can be expected to increase the pilot's control over the trajectory and can also reduce the amount of DV inadvertently applied in the event of a failed-on thruster.

Another issue for teleoperated vehicles is the reliability of the communications link with the ground. A link that is unreliable may increase the risk of collision if it fails at critical points in the trajectory (e.g., during docking operations) which could, in turn, drive a need for dynamic control regulations. However, it may be possible to reduce the significance of this issue through vehicle design. For example, safety could potentially be improved if the teleoperated vehicle is designed to perform automated hold or abort maneuvers in the event that the link to the ground fails during critical mission phases. The U.S. is currently developing such a capability for its orbital maneuvering vehicle program[5]. Two items must be noted in this regard. First, the success and acceptability of this type of capability has yet to be proven, particularly in the vicinity of manned vehicles. Secondly, successful automated abort capability will do nothing to improve the spacecraft's ability to complete the mission (i.e., the probability of mission success) in the event of a link loss. That ability will be a function of how quickly the ground recovers control and the orbital mechanics of the problem.

These concerns may not effect autonomous vehicles to the same degree as they do teleoperated vehicles, since they will presumably be designed to rendezvous and dock without nominal ground intervention. Instead, it is the reliability of such autonomous systems that may dictate the need for dynamic control. For example, if the performance of such vehicles is successfully demonstrated, crew safety might be assured by providing an abort command from the manned base. Presumably, the spacecraft could back away and the ground could assess the problem which is similar to the procedure utilized by the Soviet Progress Tanker. It should be noted that it is uncertain what effect such an abort might have on the probability of mission success, as this is undoubtably a function of vehicle capability and the orbital mechanics.

Dynamic control regulations will also be influenced by whether the unmanned vehicle will dock with the manned base, or be berthed by some manipulator mechanism. Depending upon the reach distance of the manipulator, berthing may represent less of a threat to the manned base than docking. Likewise, it will be influenced by whether the manned base is capable of performing evasive maneuvers. Such capability may also reduce the threat of collision and the need for dynamic control regulations.

The hardware and software impacts of implementing dynamic control must also be considered because it seems likely that it will require additional capability on both vehicles. For example, the manned base may require special translational and rotational handcontrollers, displays, navigation and control algorithms, and television. However, some of this equipment may be required regardless, to successfully perform other monitoring functions within the control zone. Next, consider the training and planning impacts. Dynamic control regulations will increase crew training requirements for the manned base. In addition, maintaining these crew skills may be difficult if the designated pilot is on-orbit for a long period of time prior to piloting the unmanned vehicle. Hence, onboard "refresher" training may also be required. As was noted earlier, dynamic control could also require the manned base or its ground crew to perform contingency trajectory planning. Note that these concerns may be reduced for autonomous vehicles if an abort command is utilized in place of dynamic control.

5. Parameters to be monitored

The community must decide what types of parameters must be monitored in order to satisfy safety and mission success criteria for international missions. These parameters will be partly a function of the size and regulations established for a given zone. As was stated earlier, large zones may envelop more phases of the trajectory than small ones which, in turn, may increase the number of mission management parameters to be monitored. In addition, the type of data to be monitored is probably a function of the range to the manned base. Some of the parameters to be monitored at long ranges [approximately 50 km (27 n.mi.)] may include relative position, relative velocity, and safety critical system status. At closer ranges, the manned base might also require relative attitude and direct visual sighting. Some of the issues associated with deciding these parameters are discussed below.

First, will the manned base only monitor those parameters that it can observe with its own sensors, or will it require telemetered parameters (e.g., safety critical systems data)? Assuming that there is direct voice contact between the two spacecraft, this issue may not be critical for manned vehicles interacting with the manned base. They have a crew onboard to monitor most of the same parameters that would concern the crew of the manned base. Therefore, consider the issue in terms of unmanned vehicles.

Some parameters can be obtained through either observation or telemetry. For example, relative position can be determined by the manned base's relative sensors or by telemetering data from the interacting vehicle's relative sensors to the manned base. (Note that the interacting vehicles may be required to carry some type of sensing aid, such as corner reflectors or a radar transponder to accomplish this.) In such a case, the decision of which source of data to use may be a function of the sensor array onboard the manned base. If the manned base has no relative sensor and if this type of data is critical, then telemetry may be the only solution.

Other types of data that the manned base might wish to monitor may only be obtainable through the interacting vehicle's telemetry or from the vehicle's ground control center. Safety critical systems data are a probable example. Thus, for the sake of illustrating some of the factors that influence the issue at hand, the remainder of this section discusses the need for safety critical systems data to be monitored onboard the manned base.

The need to monitor telemetry onboard the manned base may once again be a function of the communications link. If both the interacting vehicle and the manned base have highly reliable links to their ground control centers, then it may not be necessary for the manned vehicle to monitor telemetry. However, the international community will need to define what constitutes adequate reliability. In addition, it is possible that a direct communications link may need to be established between the manned base and the unmanned vehicle's control center.

If the communications links are unreliable, then lack of monitoring capability on the manned base may reduce the probability of mission success. Certain parameters must be monitored by either the ground or the manned base before a vehicle will be allowed to approach the base. It seems unlikely that an unmanned vehicle would be permitted to continue its approach if these parameters were not being monitored. The resulting abort may be difficult to recover from due to orbital mechanics, vehicle power limits, etc. In addition, contingency planning for such an abort may require additional premission and real-time planning. However, it may also be possible to improve communications redundancy by planning critical mission phases to occur over ground tracking sites. Unfortunately, this will add yet another constraint for rendezvous mission planners to contend with.

In either case, there will be hardware, software, and training impacts to be addressed. For example, if the manned vehicle does monitor the interacting vehicle's telemetry, it will need communications hardware and software, special displays, crew training to interpret the displays, etc. Without the telemetry link, additional control center links (to the ground tracking sites, etc.) and processing software may be required. In addition, lack of telemetry monitoring capability may require that the unmanned vehicle be capable of performing automated aborts to protect against loss of telemetry downlink.

Finally, it should be noted that significant time delays in processing the telemetry data on the ground may drive a need for onboard monitoring even if there is a reliable ground link. This need will be a function of the magnitude of the delay and the particular parameter in question. Safety critical parameters that can exceed their safety limits very quickly may still require onboard monitoring in order to allow the crew time to react.

6. Duration of each zone's activation

The concept of assigning control zones to manned spacecraft in orbit is relatively new and may be expected to impact both the manned base and the vehicles that interact with it. It is therefore prudent to consider whether such zones should be active continuously, 24 hours per day and 365 days each year, or whether they should be active only part of that time. There appear to be two main issues in deciding this.

First, what are the impacts on other spacecraft of having the zones continuously active? This impact is a function of many variables, and many of the technical issues have been discussed elsewhere in this paper. In summary, it seems reasonable to state that the more inclusive and restrictive zonal authority is, the more desirable it may be to limit the times during which the zone is active. That is, a large zone that requires all vehicle classes to comply with a very strict set of rules will be more of an impact to the international community than one which is not as inclusive.

Second, what are the impacts to the manned base and its mission if the zones do not apply continuously? One could make a case that the sheer value of space station-class vehicles may be such that the sponsoring nations want to maintain some authority over distances of closest approach and other factors. For example, the orbiting elements of Space Station Freedom may cost on the order of $6 billion, including the cost of their engineering development. Thus, it may be better to develop different regulations for noncritical times than to eliminate or deactivate zones. In addition, reducing the duration of zone activation may present proprietary or security concerns that are beyond the scope of this paper.

It is difficult to identify which of the hardware, software, and mission management parameter impacts are most significant in this context without having resolved some of the other issues discussed in this paper. In addition, there are undoubtably other factors that will influence this decision. Therefore, further study is required before this issue can be resolved.

7. Communications and telemetry compatibility

Communications and telemetry will be necessary to execute and monitor operations within a control zone. The data to be transmitted during future international missions may include voice, television, and data transmission. The first issue to be considered is the development of a set of communications standards for use with control zones. Such standards are necessary for two reasons: (1) to assure the establishment of a communications link and (2) to provide uniform and consistent information transfer and exchange.

Without standards for certain basic parameters, the communications link cannot be assured and many operations and safety considerations could be jeopardized. For example, the international community should agree upon the radio frequency of operations for various links (including space-to-space and space-to-ground links). Once the frequencies are allocated, their use should be regulated to avoid radio frequency interference. It should be noted that these frequencies can differ for various links. Another example of a communications parameter that should be standardized is polarization. Communications links can be implemented through linear, circular, or elliptical polarization strategies. Accordingly, coordination is necessary to ensure that the polarization of the receiving antenna matches that of the incoming wave. Similar design considerations apply to each communication link and system parameter, indicating the need for standardization to support cooperative international operations. Other such parameters include data rates, link margins, signal-to-noise ratio, radio frequency interference, modulation and demodulation protocols, and operational modes (simplex, duplex, and multiplex). Discussions leading to communications protocols for assured links should lead to an acceptable and cost-effective communications and telemetry system design to be utilized by the international community.

Standardization should also extend to parameters that affect the processing of information once the communications link is established. These parameters include carrier frequencies, data formats, and coding/decoding schemes. For example, any telemetry data received must be decoded before the data can be utilized by the system monitoring or command processing software onboard the vehicle. In the past, issues related to information exchange have been addressed by the International Telecommunications Union and the Consultive Committee for Space Data Systems. At the present time, information standards such as the Consultive Committee are emerging worldwide and these may influence the development of international standards for control zones.

The matter of adequate antennae coverage required onboard the manned base should also be addressed. Depending on the zonal regulations, coverage requirements for communications and telemetry may be a function of range (see section 5). Ensuring communications coverage at very close ranges can be more difficult than longer ranges, because the relative attitude of the vehicles becomes a more dominant factor. Omnidirectional antennae coverage could be utilized to assure proper coverage at short ranges; however, it seems impractical to implement this for an entire control zone. Various solutions can be envisioned. For example, a single control zone could be divided into several communications regions. One region might include the space within a few hundred meters of the manned base and the other might extend from this near region to a few tens of kilometers. Then, omnidirectional antennae coverage could be specified for the innermost region without severe impacts to the communications and telemetry system design. Without such a strategy, the interacting vehicle may be constrained to approach within a specific cone or region in order to fully communicate with the manned base. This approach in turn, could result in undesirable restrictions on the interacting vehicle's trajectory. Also, if several approach regions are implemented, each link may need to utilize a separate antenna to provide adequate coverage. These considerations are important for uniformity of communications and telemetry system designs for the international community.

Another issue is determining at what level communications conformity should be required. The communications hardware implementations utilized by various nations have evolved differently depending on their needs and technological advancement. One obvious step to communications and telemetry conformity would be to specify hardware designs and subsystems. However, this approach could lead to technology transfer issues and concerns. On the other hand, specification of hardware function and the resultant overall communications and telemetry performance would alleviate these concerns. For example, instead of specifying a distributed array antenna with an agile beam, one can specify the spatial and spectral coverage, and gain of the antenna and allow the implementing nation to decide an antenna configuration and type.

The international community should also determine what level of communications and telemetry system automation is required. Such automation allows fault detection and recovery and selection of the appropriate assets (e.g., receivers, antennae, transmitters) for various links. Coordination is necessary to ensure that a vehicle with automated features (e.g., selection of gains) implements the capabilities necessary to interact with vehicles that perform such functions manually. Note that this type of automated operational capability is currently being developed for possible implementation in Space Station

Freedom's communication and tracking subsystem. However, increased automation could increase the cost of hardware and software system development. The software resident on the communications and telemetry system should also be considered for mutual acceptance. Such standardization would be beneficial in the reduction of estimated program costs and could assist in contingency situations. It may also present technology transfer questions that are beyond the scope of this paper.

8. Tracking compatibility

Two issues should be addressed in order to achieve tracking compatibility. They are discussed together because they are functions of many of the same factors. First, the types of sensors that will be utilized within a control zone should be agreed upon. Second, a set of standards should be developed for the system operation parameters and hardware specifications. Table 2 is an example of specifications that have been proposed for the sensors to be utilized in U.S. space operations[8]. Other specifications could include the bands of operation, polarization, look angles, coverage, data rates, field-of-view, and data formats.

Table 2 Proposed specifications for sensors used in U.S. space operations[7]

System reliability	>0.9999
System weight	<35 kg (77 lb)
System power	<150 watts
Range resolution	≤0.5 cm (.2 in)(0 - 1 km) ≤1% R (1 - 100 km)
Range rate resolution	≤0.3 cm/sec (0 - 1 km) ≤0.002 R1/3 (1 - 100 km)
Bearing resolution	≤2 deg/R1/3 (0 - 1 km) ≤0.05 deg (1 - 100 km)
Bearing rate resolution	≤0.1/R 1/2 deg/sec (0 - 1 km) ≤0.002 deg/sec (1 - 100 km)
Sensor sample rate	≥10 samples per sec

The specific accuracies and types of data required to meet nominal and contingency trajectory and control zones requirements will influence each of these issues. Consider the choice of sensors. The Apollo Soyuz ranging and tracking equipment included optical, television, radar, docking targets, and lights. Future missions envision the use of these and other sensors. For example, infrared systems may be necessary for vehicle detection in the absence of natural or artificial light (e.g., during the dark portions of an orbit). Laser vision and laser radars are useful for determining position, velocity, and attitude with extremely high accuracy. This equipment may be required to support some docking operations. Hardware standards are similarly affected by the operational requirements. Therefore, a concerted effort should be made to standardize ranging and tracking requirements for international operations. These standardized requirements would simplify the definition of the other tracking issues.

Finally, technological advances such as automatic operation and fault tolerance will eventually become available and be implemented. These hardware implementations can result in technology transfer issues and concerns that must be addressed.

Conclusions

A control zones concept will provide a consistent foundation and an integrated framework for the development and conduct of international space operations. Initially, it can be utilized to coordinate various types of unmanned activities. The consistent framework provided by such a strategy will also support early definition of requirements for international missions. For example, the concept originally adopted for Space Station Freedom has assisted requirements definition for Europe's Man-Tended Free-Flyer.

This paper identified a broad range of issues to be considered in developing a control zones strategy. At this point it is prudent to mention some additional areas for future consideration. First, considering the high cost of activities in space, the international community may wish to define what parameters constitute grounds for aborting a mission (when they exceed their nominal ranges). Second, the issues discussed herein only considered contingencies for the interacting vehicles. The community should also evaluate the need for control zones when the manned base suffers a failure. Specifically, do zones offer any benefits then and how would the regulations change as a result? Third, this paper focussed primarily on the orbiting spacecraft themselves. However, some of the decisions to be made when establishing control zones may be influenced by impacts to existing ground facilities. Factors such as control center interfaces with other facilities must ultimately be considered.

Next, the community should examine the benefits of developing a set of standards for systems redundancy. For example, unmanned vehicles that were designed to operate with only other unmanned vehicles may not be redundant enough to satisfy safety requirements for docking with manned spacecraft. Under these circumstances, the requirements could be met by upgrading the unmanned vehicle or, conceivably, by adding the redundancy to the manned base or the ground. The availability of such standards could reduce future retrofitting of systems by specifying whose responsibility it is to provide adequate redundancy early in a program's design cycle. Finally, how could control zones be modified to support lunar bases and Mars missions? For example, it might be beneficial to assign a parking orbit zone as a holding orbit for freighters carrying lunar materials to Earth orbit.

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