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Preliminary System Design of a Three Arm Capture Mechanism (TACM) Flight Demonstration Article

April 1993

Prepared by

Otto Schaefer
Bill Stasi

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Grumman Aerospace Corporation
Bethpage, NY 11714

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1 Executive Summary

1.1 Background

Recent experience has again demonstrated the need for developing a satellite retrieval capability. The successful mission of the Endeavor shuttle flight which captured Intelsat 6 required the ad hoc resourcefulness of three astronauts standing 120 degrees apart in the shuttle cargo bay to perform the task[1]. Having an available capture mechanism which could perform this task, under supervised control, would have saved many anxious moments from all on the ground and certainly for the astronauts.

NORAD continues to follow the in-orbit object population. Of a cataloged total population of 7023 objects in space, 20 percent of these are non operational payloads and 25 percent represent mission related objects[3]. Further, only 5 percent of the catalog consists of operational payloads. Not addressed are the undetected objects which were generated from explosions or collisions. While the expected time between collisions, based on probability analysis for a nominal satellite diameter of 3 meters is still large[2], the concern for collisions between existing space debris and current and new assets grows.

Studies of the population growth and postulated debris collision models have indicated that early removal of spent flight hardware and nonfunctional payloads can reduce the rate of growth of debris in space[4]. It was further pointed out that a significant number of such objects were in range of an OMV type space based vehicle and travel in narrow bands of orbital inclination which did not require the vehicle to make plane changes. This analysis did not include the value of such a capability for evolving situations such as Intelsat 6 and cross over of debris into asset collision orbits due to interim collisions.

1.2 Satellite Retrieval Program

The overall objective of the Three Arm Capture Mechanism (TACM) is to serve as a demonstration of capability for capture of objects in space. These objects could be satellites, expended boosters, pieces of debris, etc.; anything of significant size. With this capability we can significantly diminish the danger of major collisions of debris with valuable space assets and with each other, which would otherwise produce many smaller, high velocity pieces of debris which also become concerns. The captured objects would be jettisoned into the atmosphere, relocated in 'parking' orbits, or recovered for disposition or refurbishment. The dollar value of satellites launched into space continues to grow along with the cost of insurance; having a capture capability takes a positive step towards diminishing this added cost.

The satellite retrieval development effort has been in existence at Grumman since 1987. During this time Grumman has supported MSFC in contract work which resulted in a concept selection, ground demonstration hardware design and fabrication, and performance of mission simulations in Grumman's Large Amplitude Space Simulator (Fig. 1-1). The test hardware has been delivered to NASA/MSFC for further testing; it presently is being installed for tests in the NASA/MSFC Flight Robotics Laboratory. This program has already gained much experience and information from the ground test simulations. The 'lessons learned' have been applied to current study efforts as well as other ongoing programs that investigate automated rendezvous and docking of spacecraft. Many of the issues originally identified as requiring resolution prior to committing to flight hardware (Fig. 1-2) have been addressed in varying degrees in the ground simulation testing performed.

The effort covered by this report is a planning step towards a flight demonstration of the satellite capture capability. Based on the requirement to capture a communication class satellite, its associated booster, or both, a preliminary system definition of a retrieval kit is defined. The objective of

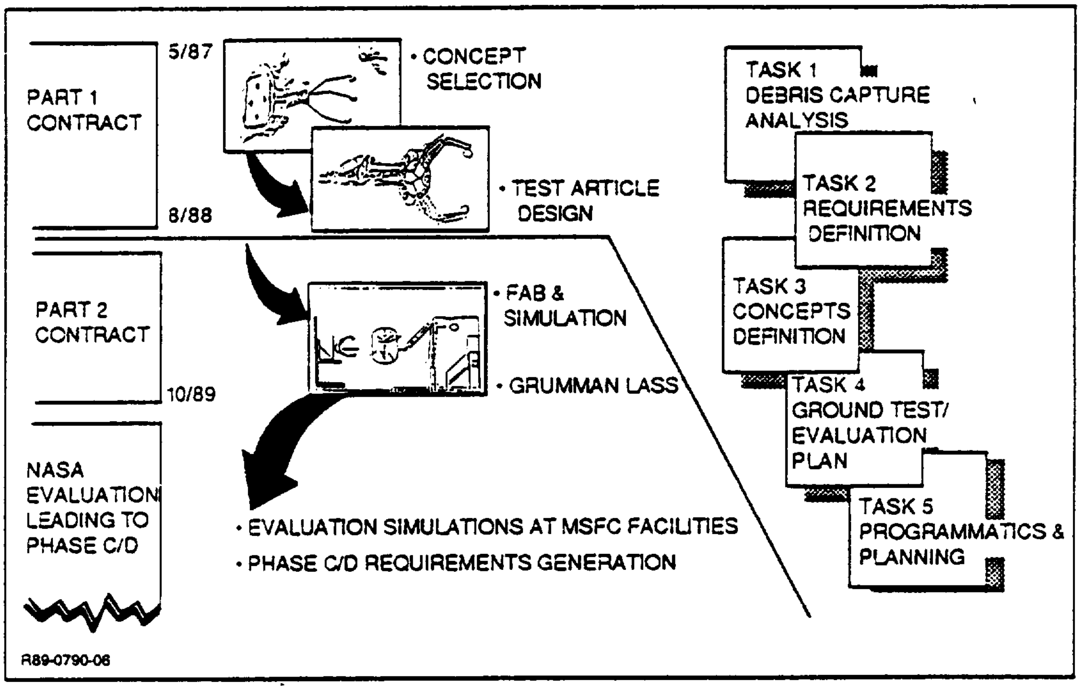

Fig. 1-1 Overview - Concept Evaluation/Test for the Satellite Retrieval Kit (teleoperated mission basis)

Issue	Resolution Approaches		
	Analysis	Ground Simulation	Flight Experiment
Debris characteristics (physical & dynamic)	√		
SAT characteristics (physical & dynamic)	√		
Capture interface and mechanism design	√	√	
Capture technique	√	√	√
Capture object transport technique	√	√	√
Spin/despin interface design	√	√	
Extension arm(s) design	√	√	
OMV thrust vector & control authority	√	√	
OMV protection approach	√	√	
Retrieved capture subject handoff approach	√	√	√
Time delay operations	√	√	√
Autonomous vs tele-op control mix	√	√	
Control system design and integration	√	√	
Viewing and lighting requirements	√	√	√
Number/variety of kits	√		
Kit modularity level	√		
Reconfiguration capability during flight	√	√	
Hazards handling and avoidance	√	√	
Abort capabilities & methods	√		
Deorbit techniques and systems	√	√	√

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Fig. 1-2 Flight System Issues & Approaches to their Resolution

the flight demonstration is to demonstrate the techniques proposed to perform the mission and to obtain data on technical issues requiring an in-situ space environment. The former especially includes issues such as automated image recognition techniques and control strategies that enable an unmanned vehicle to rendezvous and capture a satellite, contact dynamics between the two bodies, and the flight segment level of automation required to support the mission.

A development plan for the operational retrieval capability includes analysis work, computer and ground test simulations and finally a flight demonstration. This document describes a concept to perform a selected mission capturing a precessing communications satellite. Further development efforts using analytical tools and laboratory facilities are required prior to reaching the point at which a full commitment to the flight demonstration design can be made.

1.3 Flight Demonstration Preliminary System Design

The system design for the demonstration hardware focuses on the following objectives:

- identify the elements of the capture mechanism that are required to perform capture of a communications class satellite or associated booster in free space
- consider a broader set of capture missions to ensure the problem selected is not too restrictive
- perform top level assessments and analysis work to develop strategies to accomplish the mission
- use existing and emerging technologies to develop design information that will allow a first order estimate of a configuration, size, power requirements, weight, and significant near term work efforts to support the objective.

The concept proposed is a mechanism which has automated features that will allow it to grasp the precessing satellite. The mechanism is attached to a host vehicle for transport and rendezvous movements and also for power and communications with a ground station.

As proposed, our design may be compatible with two types of host vehicles, the shuttle and an unmanned propulsion platform. Figure 1-3 shows the design connected to the unmanned propulsion platform. The three arm capture mechanism (TACM) is composed of three two link arms, each having radial movement and collision sensor capability at their respective tip sections. Each tip section also has a fast actuator and laser ranging sensor that facilitates radial motion matching with the satellite just before contact. The three arms are mounted on a spin table which provides rotational motion for matching capability and alignment with spinning/precessing satellites. An image recognition system is mounted on the spin table to perform operations that will direct the vehicle approach to the satellite in the most desirable orientation for capture. The structure to which both of the above parts are mounted contains the required capture control computer processing equipment, a spin motor with signal and power processing and interfacing equipment. The structure is mounted to the host vehicle which provides the maneuvering capability.

The TACM will have the capability to capture communication class satellites and their respective final stage boosters. The TACM has 12 foot arms and weighs approximately 1200 pounds. The former weight estimate is to be considered a rough order of magnitude estimate pending design analysis which respond to contact dynamic loads based on satellite capture requirements and stipulated host vehicle configuration. While a contingency figure has been added to the weight estimate, specific support items such as thermal control, redundancy have not been addressed at this time.

An alternate arrangement attached to the shuttle is shown on Figure 1-4. The TACM is shown attached to a more robust, stiff version of the RMS which is installed onto the cargo bay structure. We have reviewed the

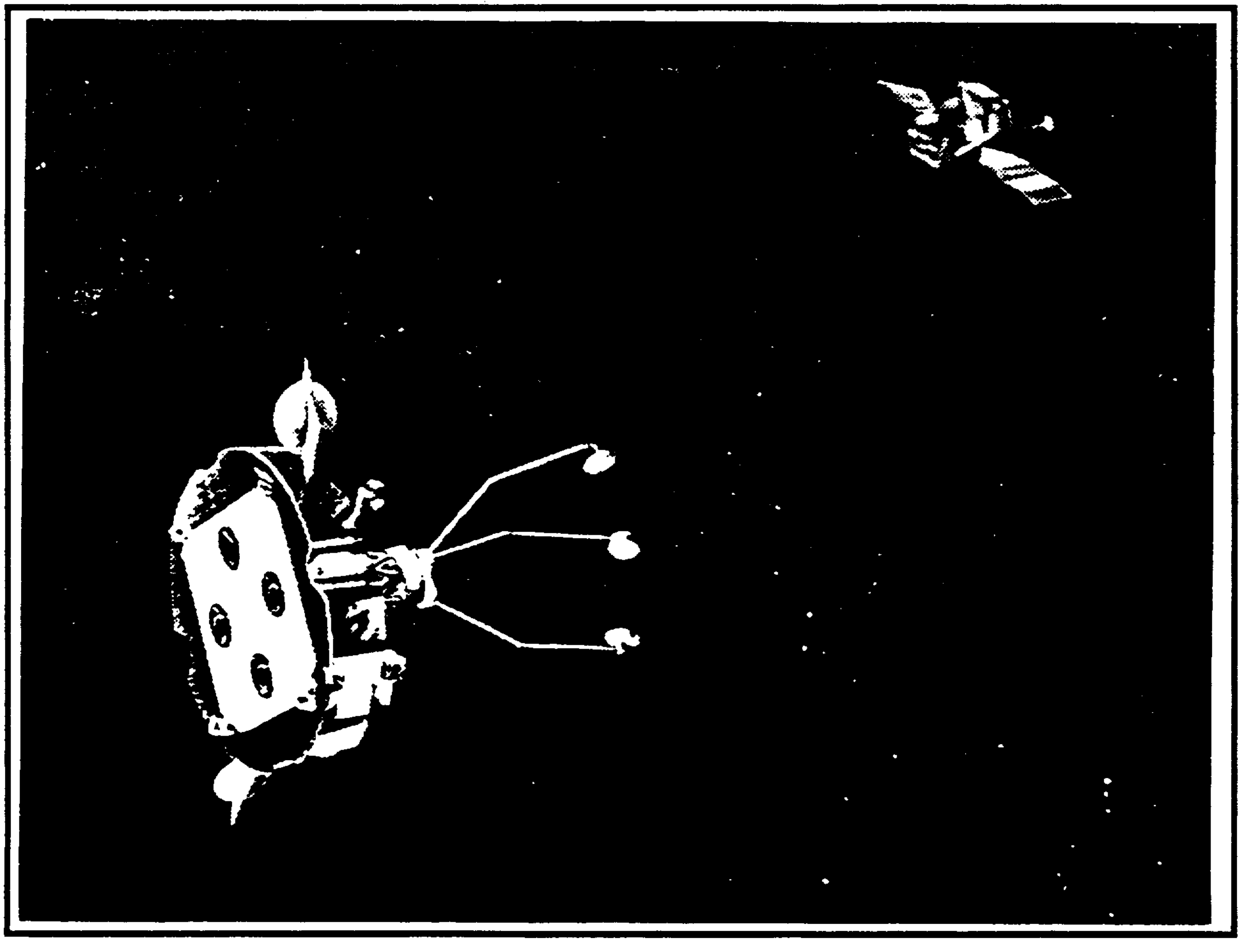


Fig. 1-3 Three Arm Capture Mechanism (TACM) Attached to a Host Propulsion Vehicle

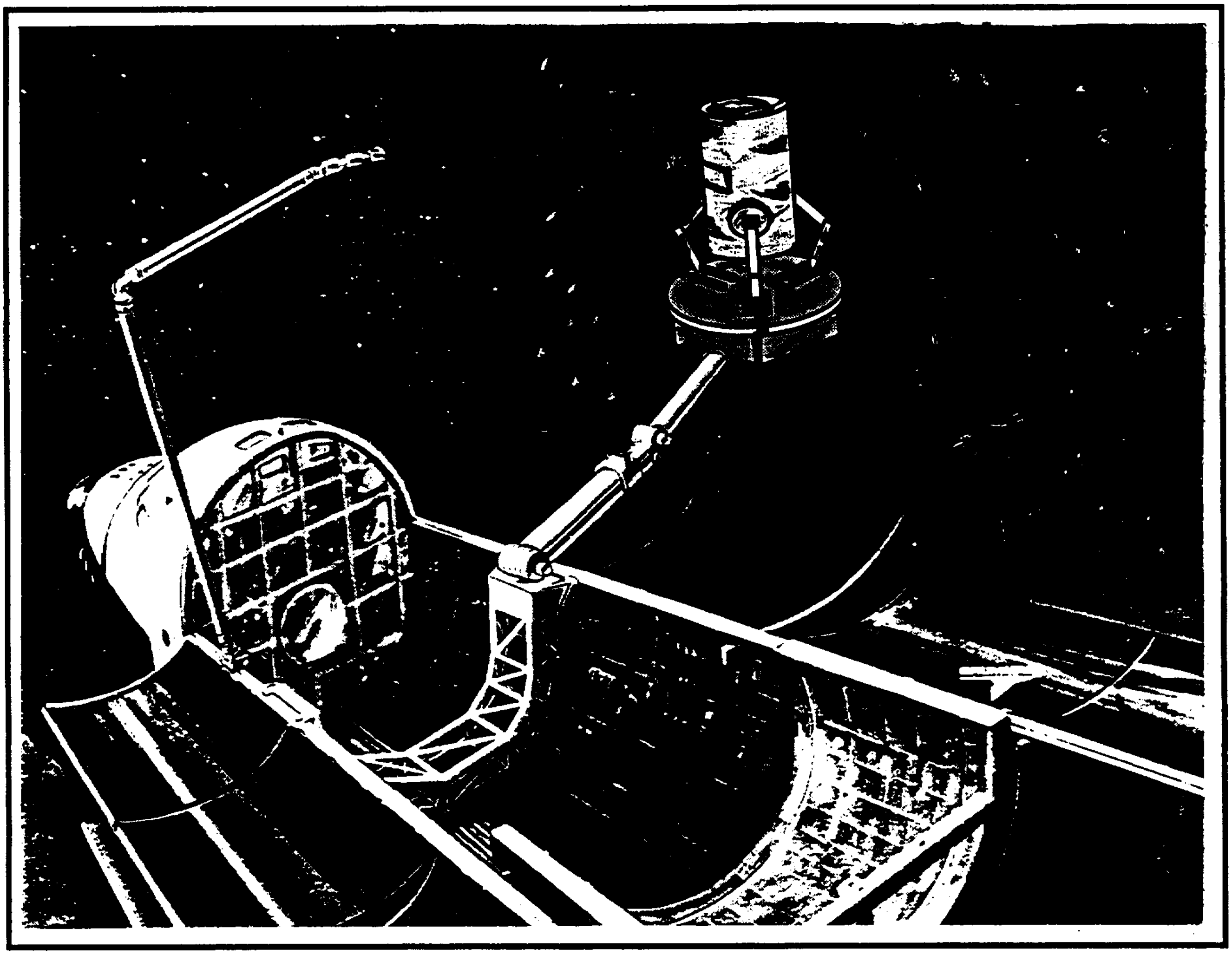


Fig. 1-4 Satellite Retrieval Using the Shuttle as a Host Vehicle

possibility of capturing the Intelsat 6 which was spinning at 0.2 RPM using the present RMS. The TACM would be attached to the end of the RMS using a standard payload grapple fixture. Given that spin rate and the fact that the minimal precession was involved (giving rise to small contact load perturbations), we conclude the TACM could have been used to perform the capture mission. The RMS standard servicing capability[12] includes a payload that is four times the mass of Intelsat 6. When fully extended, the RMS has the capability of generating control forces of 230 ft-lbf torque about the roll (longitudinal) axis. When the arm is not fully extended, significantly higher forces may be applied to payloads. The estimated momentum that must be resolved to bring the satellite and TACM to rest is in the order of 107 ft-lbf, which is reasonably within the design margins of the RMS assuming that no time constraints force rapid deceleration.

2 Design Basis Mission

2.1 Background for Mission Scenario

The objective of the demonstration mission is to capture a communications class satellite or its associated booster. In case the NSTS Manifest would not allow scheduling the demonstration or if detail objectives were better suited to be met by a self contained remote propulsion system, two mission bases have been used to guide this study; one predicated on the use of the shuttle and an RMS type handling structure and one using an unmanned vehicle. The former could take the form of a booster or a propulsion platform such as the planned OMV or variation of the existing Minuteman fourth stage vehicle.

To define the target satellite motion and configuration features that should be included as part of the demonstration, we considered characteristics of communication satellites in orbit and those presently in the planning stage, and also information on the boosters used for final orbital placement. The important parameters were identified and then a mission scenario demonstrating capture under a prescribed target satellite condition was developed.

Communication satellite capture opportunities occur in two space regimes: LEO, for those satellites which have not attained their operational orbit because of system malfunctions; and GEO, for cases where the satellite did not arrive at the proper orbital location, a malfunction, or the case of end of life retrieval/transport. A low earth orbital location was selected for the demonstration scenario to facilitate use of the shuttle either as a payload carrier or an active part of the demonstration (i.e., RMS). A LEO location also provides a better basis for analyzing mission events, is less costly and also does not have the added burden of GEO communication system time delay effects (even though this mission is to be based on automated operation). In each mission case we assumed that the host vehicle was able to provide and maintain desirable attitude control with the selected axis of the target spacecraft; requirements that effected the capture mechanism performance are addressed.

2.2 Characteristics of the Demonstration Mission Target

This effort, based on investigating capture of a communications class satellite and/or its associated booster, has reviewed pertinent characteristics of these components and draws some conclusions relative to a selected candidate. Owing to the demonstration nature of the mission, it is suggested that a candidate of reasonable size and mass be chosen, not specifically the largest and heaviest. Technology issues must still be resolved and "lessons learned" applied to the design; resolution of issues may be easier demonstrated on more standardized shapes, albeit of reasonably similar size shape and mass.

2.2.1 Communication Class Satellites

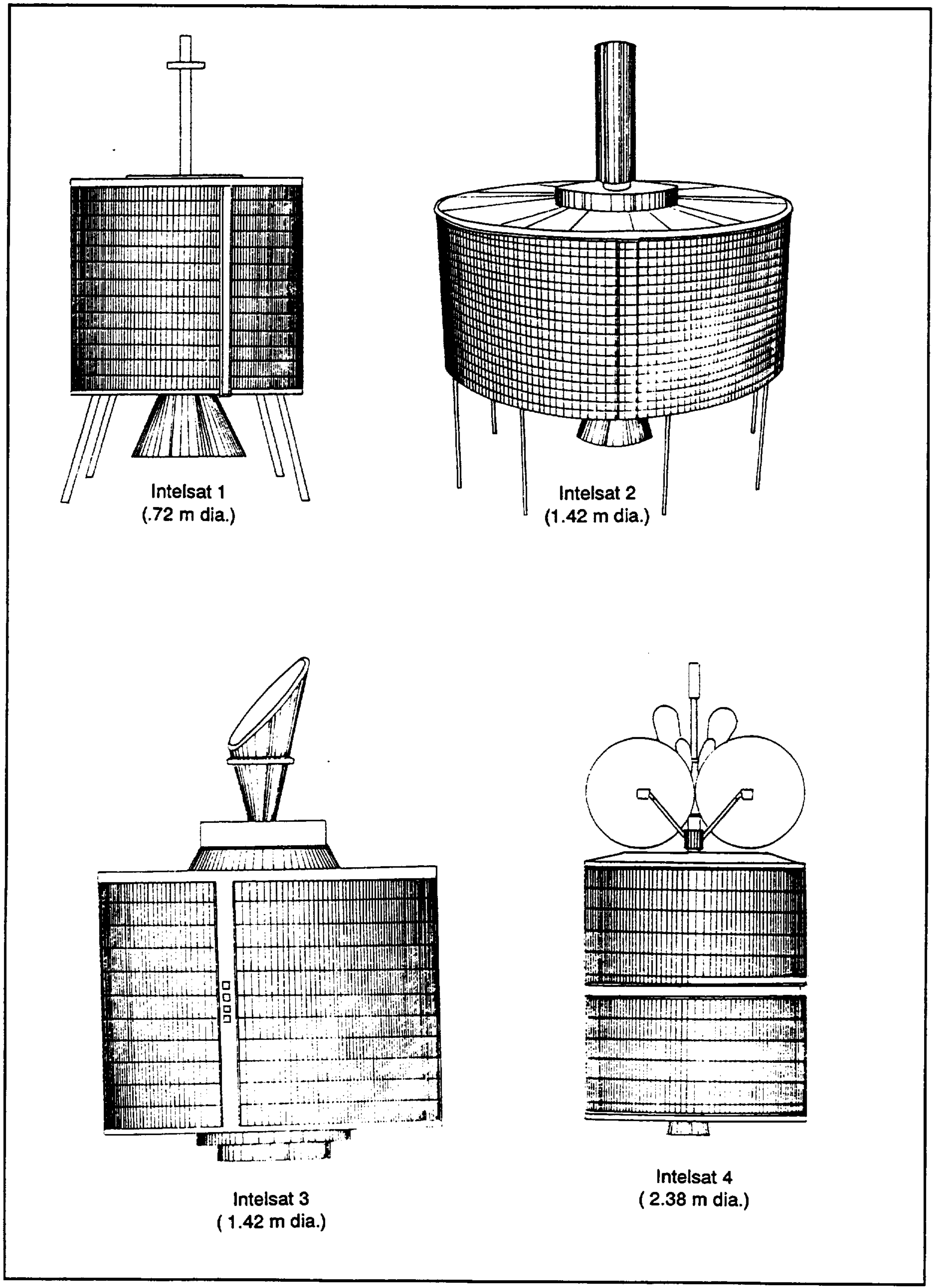
A summary of major communications satellite characteristics , with a focus on those manufactured by Hughes (source for most Intelsats) are presented in Fig. 2-1. They are operationally located in GEO; are mostly cylindrical; and are mostly spin stabilized, with the top portion, which contains the transmitting antennas, despun.

The Intelsat class satellites come in various sizes. All except the most recent one which is in the planning stage, and Intelsat 5, are cylindrical and are spin stabilized.

At end of life, the more recent satellites contain residual propulsion for relocation to a more remote orbital position. The earlier satellites remain in position with both portions (despun and spinning sections) gradually slowing down first to a composite average rotational speed about the major axis and then slowly decreasing.

Satellite Series	Satellite Name(s)	Picture Reference	Manufac'r.	Number of Series in Orbit	Initial Weight on station (kg)	Main Body Dimensions	Appendage Description	Location	Operational Motion Condition	Booster(s) Used
Intelsat 1	(Early-bird)	See sheet 2 of 4	Hughes	1	39	.72 m dia. x .59 m high	antenna & nozzle	GEO at 325 deg. E longitude	spin	Thrust Augmented Delta
Intelsat 2	F-1 to F-4	See sheet 2 of 4	Hughes	4	86	1.42 m dia. x.67 m high	antenna & nozzle	F-1 failed to reach GEO, other in GEO	spin	NA
Intelsat 3	F-1 to F-8	See sheet 2 of 4	TRW	8	152	1.42 m dia. x 1.04 m high	NA	F-1 & -8 failed to reach orbit, F-2 incorrectly positioned, others in GEO	spun & despun sections	Delta
Intelsat 4		See sheet 2 of 4	Hughes	7	732	___ m dia. x 5.26 m high (2.81 m stowed)	Receive & transmit antennas	GEO	spun & despun sections	Altas Centaur
	intelsat 4A	See Intelsat 4	Hughes	6	862	2.38 m dia. x 6.78 m high (2.81 m stowed)	Receive & transmit antennas	GEO	spun & despun sections	Altas Centaur
Intelsat 5	Intelsat 5, 5A	See sheet 3 of 4	Hughes, Ford	9	825, (10th is 5A)	6.6 m high w/ body of 1.66 m x 2.01 m 1.77 m	solar panels 15.6 m long	GEO	3 axis stabilized	Altas, Centaur
Intelsat 6	Intelsat 6 F-2	See sheet 4 of 4	Hughes	5	22231, (1901 dry mass)	3.6 m dia. x 5.3 m high	Receive & transmit antennas	GEO	spun & despun sections	Ariane, LAM
	Intelsat 6 F-3 (Endeavour resue)	See sheet 4 of 4	Hughes	5	4070			GEO	spun & despun sections	2-stage Titan, Orbus 21S
HS-376	HS-376 [SBS1-5, Aussat A1-3, Telstar 301-302,Westar 6, Palapa B1,b2p,etc. Galaxy 1-3, Wesstar 4&5, Brazilsat]		Hughes	37	550 to 700	2.16 m dia. x 6.6 m high (2.84 m stowed)	1.82 m high Receive & transmit antennas	GEO	spun & despun sections	2-stage Titan, Thiokol Star 30 solid apogee kick motor; Delta; shuttle w/ PAM-D
Intelsat 7	planned	see Intelsat 5	Ford	5 scheduled	1800, 1425 dry	similar to Intelsat 5	similar to Intelsat 5	GEO	3-axis stabilized	Atlas 2AS, Ariane 4

Fig. 2-1, sheet 1 of 4 Summary of Communications Class Satellites



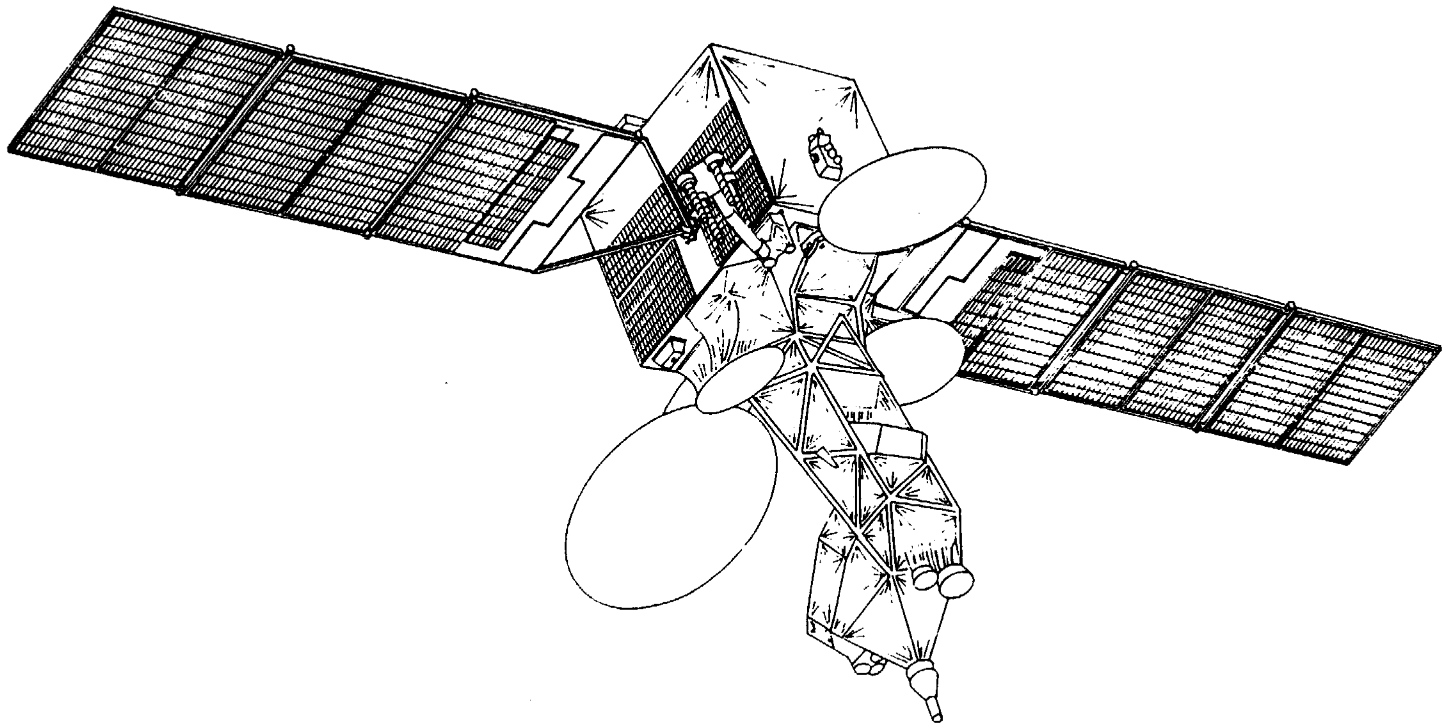
Intelsat 1
(.72 m dia.)

Intelsat 2
(1.42 m dia.)

Intelsat 3
(1.42 m dia.)

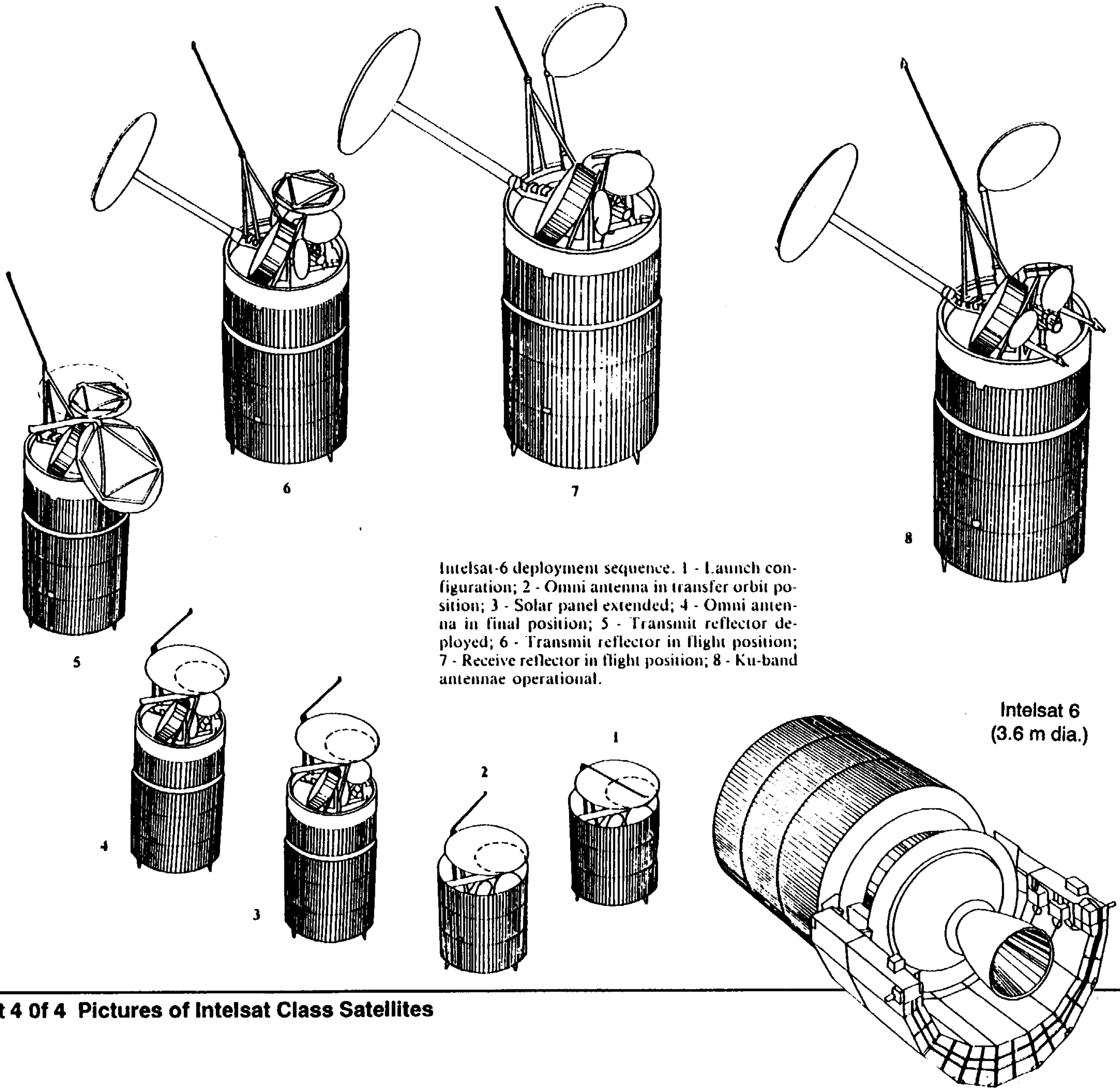
Intelsat 4
(2.38 m dia.)

Fig. 2-1, sheet 2 Of 4 Pictures of Intelsat Class Satellites



Intelsat 5
(1.66m x 2.01 m x 1.77 m high)

Fig. 2-1, sheet 3 0f 4 Pictures of Intelsat Class Satellites



Intelsat-6 deployment sequence. 1 - Launch configuration; 2 - Omni antenna in transfer orbit position; 3 - Solar panel extended; 4 - Omni antenna in final position; 5 - Transmit reflector deployed; 6 - Transmit reflector in flight position; 7 - Receive reflector in flight position; 8 - Ku-band antennae operational.

Intelsat 6
(3.6 m dia.)

Fig. 2-1, sheet 4 0f 4 Pictures of Intelsat Class Satellites

As shown by Fig. 2-1, the mass and size of communication satellites have increased in response to requirements and technology advances. In general, there is very little solid frame structure on the lateral cylindrical surface. The load bearing surface, in general is the bottom face of the permanent satellite surface; the more current designs (Intelsat 6) have an additional section of solar panels telescoping from the bottom of the satellite. The major axis is almost always perpendicular to the direction of earth nadir. Currently, more of the future, high technology designs appear to be on a 3-axis stabilized basis.

A Focus on Intelsat 6

In the following paragraphs we discuss the Intelsat 6 and its capture, performed as part of a 1992 shuttle Endeavor space EVA. Three astronauts, standing 120 degrees apart in the shuttle cargo bay grasped the satellite and brought it under control. The information is based on telephone discussions and documentation from the satellite manufacturer and also the mission support staff at NASA/JSC.

Intelsat 6, and the Intelsat class satellites in general, are manufactured with the cylindrical surfaces comprising solar cell arrays (See Fig. 2-1, Sheet 4 of 4). The solar cell surfaces are not fabricated to be load bearing surfaces and are not to take radial loads. Any significant radial pressure (guess at 5 pounds per square inch) will probably damage the cells, and may even penetrate the surface. As indicated in Fig. 2-2, the satellite is 143.3 inches in diameter and 172.4 inches in length. The center of gravity 41.1 inches from the lower (more accessible) end. The weight and moments of inertia are as follows:

Weight = 8697.8 pounds

I_{yy} = 4993 slug-ft^2 | I_{yz} = 4.1 slug-ft^2

I_{zz} = 4502 slug-ft^2 | I_{yx} = 12.3 slug-ft^2

I_{xx} = 4444 slug-ft^2 | I_{zx} = 53.2 slug-ft^2

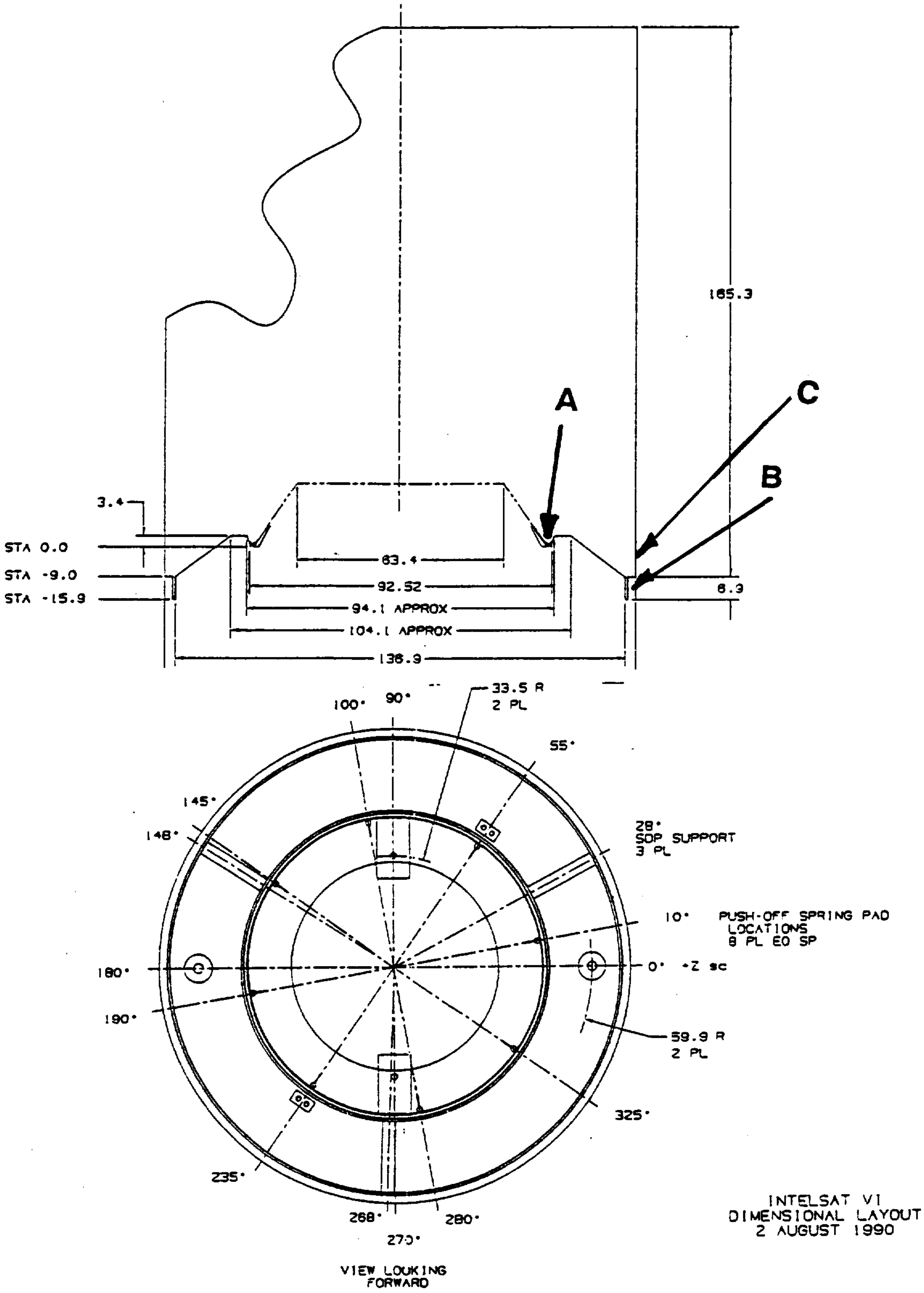


Fig. 2-2 Intelsat 6 Envelope Dimensions

There is a three point frame for the satellite inside the solar array surface, running along the length of the cylinder. The Intelsat 6 was built with an extendible section of solar cell area, a shell that slides out from behind the lower main array area. See Figure 2-1, Sheet 4 of 4. This extension may not be retractable. The lower portion of the permanent array area has some rigidity, but it was not the initial target contact area for the astronaut mission. The astronauts planned to attach a fixture to a ring surface inboard of the lower circular face of the satellite. Refer to Figure 2-2, location reference A. The interface ring was determined to be one of the sturdiest locations on the spacecraft and capable of bearing all anticipated program related loads. When the capture operation did not work, because insufficient pressure could be exerted on the satellite to actuate the mechanism on the interface ring without the satellite moving away, other avenues were attempted. The satellite surface zones that previously were not to be touched (because of a fear of damage to the solar cells) became acceptable touch zones. The astronauts used the ring surface that extended beyond the lower permanent solar cell area as the primary holding surface (See Figure 2-2, location reference B). This ring is composed of a thin titanium sheet approximately 7 inches in length. Its purpose is to support the solar array extension motors and guide the extension downward. This surface, together with the solar drum positioning units proved to be sufficiently rigid for grasping and handling the large satellite in a space environment. Data from accelerometers located on the satellite indicated that only micro-level accelerations were imposed on the satellite during the capture operation.

The initial contact made with the satellite by the astronaut produced a yaw movement to the right. A final spin rate of 0.2 RPM was reported prior to its capture by the astronauts.

2.2.2 Booster Parts in Orbit

The spent upper stages that transport satellites into geosynchronous Earth orbits (GEO) are left in stable elliptical orbits[1]. These spent stages have perigee altitudes of about 300 km and apogee altitudes of about 35,800 km. Because their orbital path crosses both the geosynchronous region as well as low Earth orbit (LEO), it represents a hazard in both.

The stages that are representative of the population are summarized in Figure 2-3. The significant characteristics for our capture problem are the mass, size, magnitude and variation in moment of inertia in the three axis. The largest nominal diameter is about 120 inches, slightly smaller than the largest Intelsat. The dry weight (fuel expended) are of the same order of magnitude as the satellite; fully loaded, the weight is considerably higher.

Figure 2-3, Sheets 2 to 4 show the physical configurations of some of the stages.

Work on predicting the rate of spin rate decay of objects in space has been initiated by NASA/JSC. Population data is being compiled by Carl Henize. He referred to work being performed in Germany which includes optical observations of spin decay characteristics in LEO. A theory was offered by another expert in the field of space debris that the residual spin mode may even be promoted by the earth's magnetic field; his calculations show that a final spin rate of about 5 RPM is possible.

2.2.3 Selection of a Target Satellite Configuration and Spin Condition for use in the Demonstration

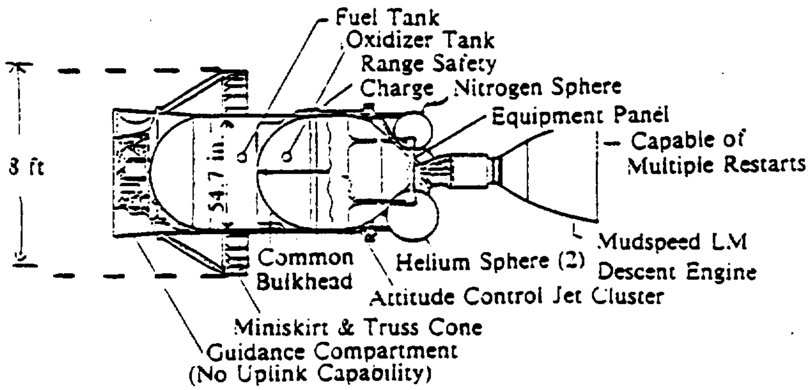
It is proposed that a target equivalent to the size and mass of Intelsat 6 be selected. A spin condition of 5 RPM and nutation angle of 5 RPM was selected. The following paragraphs discuss the rationale for our selection.

<u>Consideration of Scale</u>

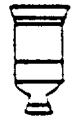
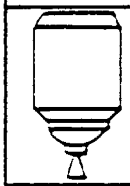
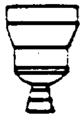
It has been our experience that satisfactory results using scale model testing involving the complexities of our technologies are easier attained if the test simulation scale is no less than about 50 to 33 percent of full size. As the

Final Stage Booster Name	Launch System	Final Stage Manufact'r	Final Stage Gross Weight (pounds)	Final Stage Dry Weight (pounds)	Final Stage Envelope Dia. x length
Centaur	Atlas I	GD	34300	4300	3.05 m x 9.15 m
Centaur	Atlas II	GD	41500	4500	3.05 m x 10.1 m
Centaur IIA	Atlas IIA & IIAS	GD	41800	3800	3.05 m x10.1 m
Centaur	Titan IV	GD	52600	7800	4.3 m x 9.0 m
PAM-DII	Titan III	Mac Dac	7695	555	1.6 m x 2 m
Transtage	Titan III	Martin	29780	6890	3 m x 4.5 m
TOS	Titan III	OSC/Martin	23800	2400	3.4 m x 3.3 m
IUS (stage 1/stage 2)	Titan IV	Boeing	23960/8600	2560/2540	2.9 m x 5.2 m
Centaur	Titan IV	General Dynamics	52600	7800	4.3 m x 9.0 m
3rd stage (PAM-D motor) -6925	Delta	McDonnell Dougles	4721	291	1.25 m x 2.04 m
3rd stage (PAM-D motor) -7925	Delta	McDonnell Dougles	4721	291	1.25 m x 2.04 m
Ariane 3rd Stage	Ariane 4	CNES	26700	2900	2.6 m x 9.9 m
L7	Ariane 5	CNES	2000		5.4 m x 4.5 m
Centaur	Atlas I	GD	34300	4300	3.05 m x 9.15 m
Centaur	Atlas II	GD	41500	4500	3.05 m x 10.1 m
Centaur IIA	Atlas IIA & IIAS	GD	41800	3800	3.05 m x10.1 m

Figure 2-3 Sheet 1 of 4 Summary of Final Stage Boosters

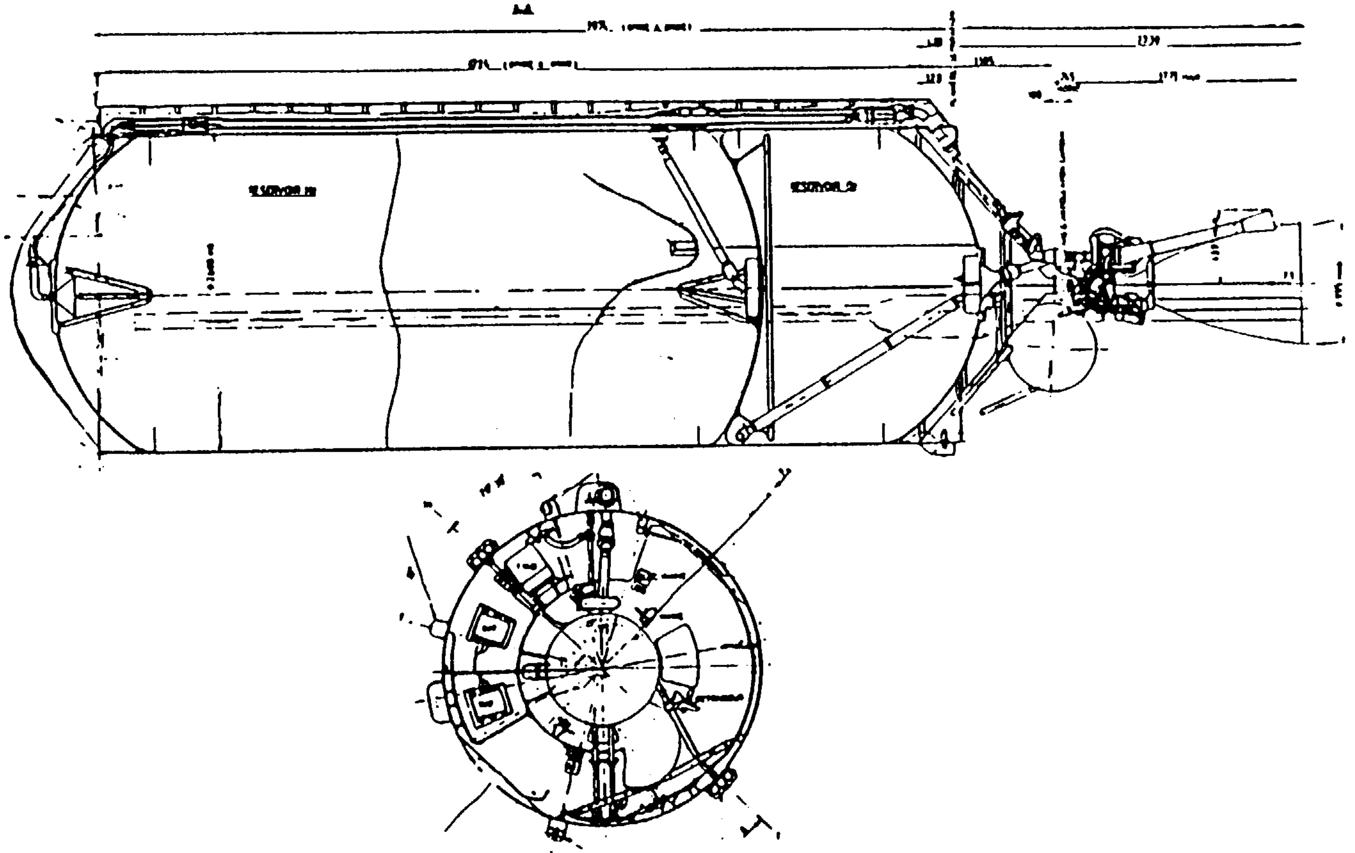


Delta 3910 second stage. Dry mass. ≈ 1800 lb. Insulation blankets not shown.

	Inertial Upper Stage	Builder: Propulsion:	Boeing United Technologies SRM-1 and SRM-2 Solid Motors
	Centaur G-Prime	Builder: Propulsion:	General Dynamics 2 Pratt & Whitney RL10A-3-3A Liquid Motors
	Transfer Orbit Stage	Builder: Propulsion:	Martin Marietta (for Orbital Sciences Corporation) United Technologies SRM-1 Solid Motor
	Payload Assist Module (PAM)	Builder: Propulsion:	McDonnell Douglas PAM-D, Thiokol STAR 48 Motor; PAM-DII, Thiokol STAR 63 Motor
	Expendable Shuttle Compatible Orbit Transfer System (E-SCOTS)	Builder: Propulsion:	General Electric Astro Space Thiokol STAR 63F Solid Motor

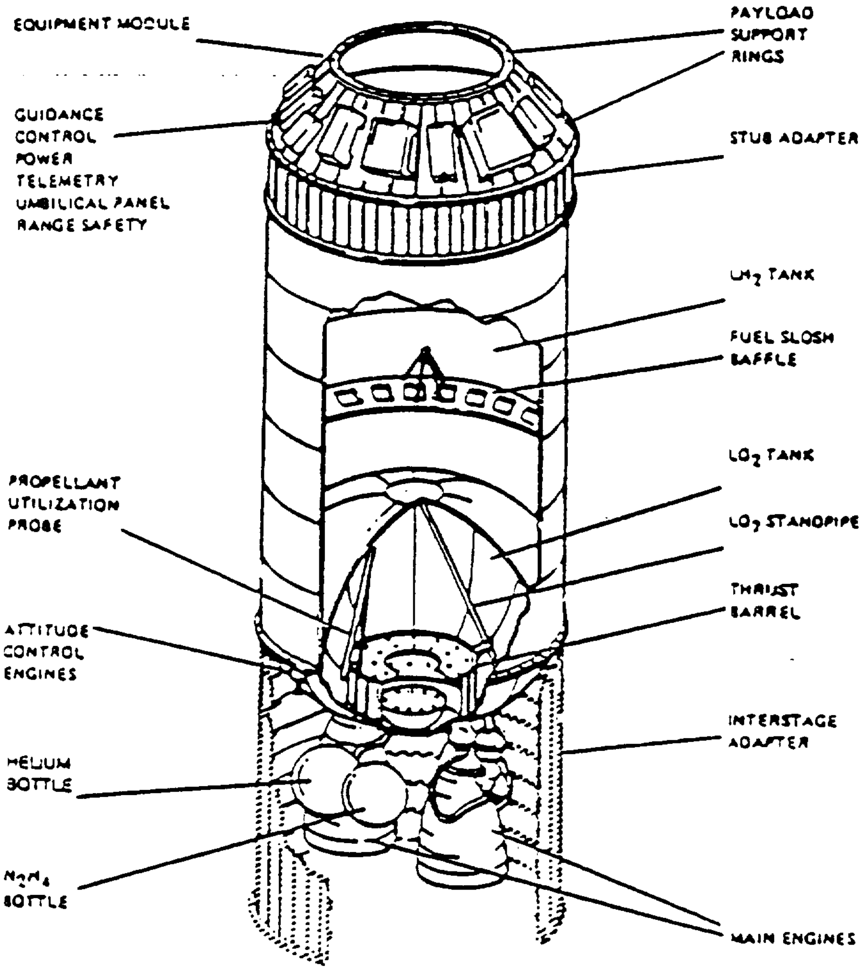
Upper Stages

Figure 2-3, Sheet 2 of 4 Summary of Final Stage Boosters



Ariane third-stage views.

Figure 2-3, Sheet 3 of 4 Summary of Final Stage Boosters



Centaur vehicle arrangement.

Figure 2-3, Sheet 4 of 4 Summary of Final Stage Boosters

kinds of independent sensors suites that operate in a concurrent and integrated manner increase, cross effects in the laws of similitude must be examined. Using teleoperation, the operator can perform a large number of functions, accommodating the differences due to scaling. In our proposed conditions of automation, we are integrating the outputs of many different types of sensors: force; image sensor data; laser range information to support CAD modeling, distance sensing, and collision control; spin rate for motion matching; and servo control inputs to maintain vehicle stability. Camera and pixel processing capability will be specifically tailored for the demonstration. Also since this is to be a demonstration mission, it is very important to exclude as much uncertainty as possible and include realistic parameters so that flight component selection and technology level readiness can be verified.

Size and Weight

The diameter of this proposed target vehicle is representative of the largest within the communication satellite class. Its dry weight is indicative of a booster spent weight, the Intelsat 6 also will provide a fairly representative model of that type of vehicle. Only the case of capturing a satellite still attached to its booster would provide a more extreme demonstration case. The ability of the TACM to accommodate such off-nominal cases can be analyzed as part of future activities.

Intelsat 6 represents a target model of a cylinder with smooth cylindrical surfaces and an accessible bottom surface area. The top portion of the actual satellite is not considered accessible due to protruding appendages (although we may find that the selected capture arm size may facilitate approaching from this direction also). For our capture case, we plan to grasp the satellite with as much care as possible at points which offer some rigidity and substrate support. From a communication satellite owner's point of view, no such point exists on the cylindrical surface, so performance of such a capture mission would include risk to the solar cells. We would therefore plan on two potential areas:

- the lowest part of the permanent solar array, from which the extension is drawn. See location reference B in Figure 2-2. This capture point is about 41.1 inches from the major axis center of mass.

- in a plane where the satellite support frame is located along the length of the satellite. The depth is dependent on the size of the capture arms and degree of nutation of the satellite; we need to reach around the lower surface, which represents the plane of maximum travel. From a preliminary investigation it appears that the TACM concept can reach 65 inches along the satellite lateral dimension.

We will however maintain a generic view on depth penetration, since the capture orientation and control strategy is not a function of where on the lateral surface we capture the satellite.

Rigidity

We are basing our proposed methodology on the fact that the surface and substrate will provide adequate rigidity to perform capture and then to facilitate transport. Additional data and probably testing or modeling must be performed to support our postulated methodology; for purposes of conceptual planning and establishing a baseline for a demonstration mission, we believe our proposal will suffice. "Lessons learned" information mandates that we plan on matching motion with the satellite and minimize the relative initial contact force (impulse) and ensure that all capture arm contact is coordinated and are applied simultaneously and in a consistent manner. Beyond that, the capture pad should be as big as possible and conform to the surface to minimize the contact pressure and spread out the load effect.

Motion Condition

Previous work has investigated the issues encountered in capture of satellites in pure spin around their major cylindrical axis. Grumman has performed test simulations of that problem on a teleoperation basis. In this capture mode, an operator takes an active role in all motion matching and capture movements of the mechanism.

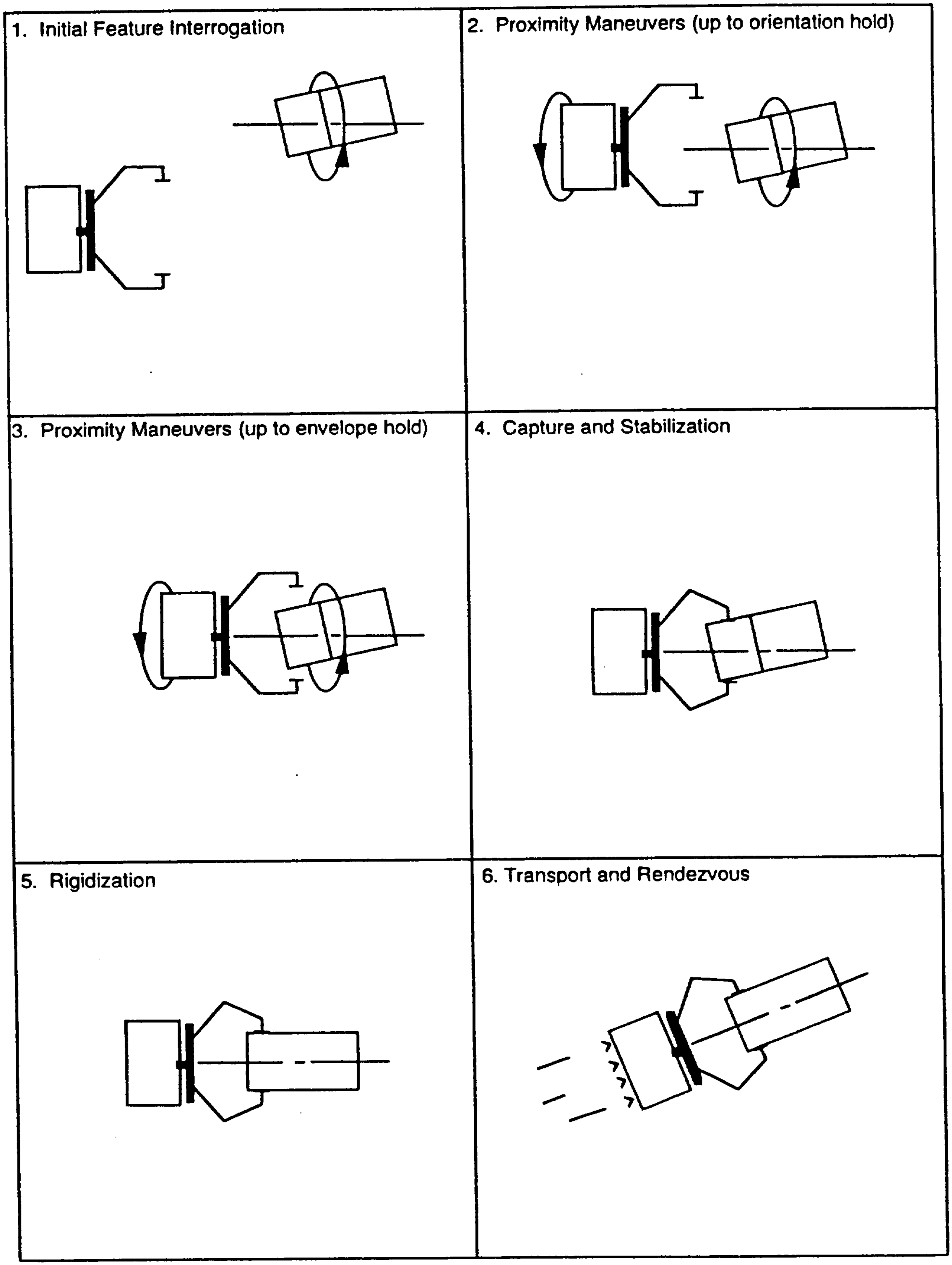
It is realistic to postulate that the target satellite will have a motion condition along a major axis. Previous study work and observations in space have verified that spinning objects gradually reduce to major geometrical axis spins. For demonstration purposes we will assume a reasonable precession condition far greater that the Intelsat capture condition. This will demonstrate the control technique required on a more generic basis.

2.3 Mission Scenario

The scenario that was used to identify the step operations for using the three arm capture mechanism (TACM) to perform satellite capture and define the system for the demonstration mission is described below. Information on how the equipment and TACM mounted sensors are to be used in the capture process is also included. This level of detail aids the component specification task and provides shape to the scenario mission timeline. A overview of the entire scenario is depicted in Figure 2-4.

The target satellite is assumed to be an Intelsat 6 satellite spinning slowly with precession.

The TACM is attached a host vehicle which is assumed to have the navigation and positioning capabilities to position the TACM within range of the image recognition system to interact with the target satellite and initiate the capture mission. The host vehicle is responsible for rendezvous and far term proximity operations with the target satellite. The TACM is composed of three two-link arms which each have radial tip control. The TACM is equipped with a suite of sensors that includes an image recognition system and a companion base mounted laser ranging sensor, three arm-mounted laser ranging sensors and pressure sensitive pads at the



1. Initial Feature Interrogation

2. Proximity Maneuvers (up to orientation hold)

3. Proximity Maneuvers (up to envelope hold)

4. Capture and Stabilization

5. Rigidization

6. Transport and Rendezvous

Figure 2-4 TACM Satellite Capture Scenario

tips of each arms.

The desirable level of supervised automation for this mission, would be characterized by the use of hold points where the mission control operator has the opportunity to take abort action, instruct the device to continue the planned action sequence, or take alternative action.

2.3.1 Initial Feature Interrogation

This step starts at approximately 50 feet from the target vehicle and includes initial inspection movements. It is anticipated that the host vehicle/TACM will move closer to the target during these operations.

Once the operability of the TACM systems has been verified and initial mapping has provided positive correlation to a CAD model, a status signal is transmitted to the ground station.

2.3.2 Proximity Maneuvers (up to orientation hold)

This task includes all maneuvering required to establish a desirable TACM hold position with the target satellite. Orientation hold is defined as having the TACM along the desired satellite approach vector (i.e. a selected target satellite spin orientation axis). The position of the TACM/host vehicle at the orientation hold point is approximately two diameters away from the target vehicle. See Figure 2-4.

The TACM provides control maneuvering directions to the host vehicle processor to continue movement until the TACM is aligned along the desired approach vector. The maneuvering process continues based on TACM commands to the host vehicle for maneuvering jet firings. A preprogrammed approach vector profile which minimizes thrusting in the direction of the target vehicle is used. The image mapping system also continues to update its data base during the maneuvering process and provides updated inputs to the TACM processor to improve alignment with the selected satellite axis. The distance sensor system located at the base of the TACM supports the image mapping process and provides the information to establish that the TACM is at the desirable orientation match conditions.

2.3.3 Proximity Maneuvers (up to envelope hold)

This task includes all maneuvering and TACM movement required to establish an envelope hold position with the target vehicle. Envelope hold is defined as having the TACM along the desired approach vector, spinning at the selected satellite spin rate, at the desired capture depth along the lateral surface of the satellite cylindrical surface but outside of its motion envelope. See Figure 2-4.

Upon receipt of authorization from the ground operator to proceed from "orientation hold," the TACM spin table is actuated and rotates the TACM assembly to match motion with the target satellite spin rate. The spin rate command is derived from the results of the image recognition system modeling. Once stabilized, a status signal is transmitted to the ground station for authorization to proceed to envelope hold. The TACM provides control maneuvering commands to the host vehicle processor to proceed along the desired approach vector towards the target satellite. The maneuvering process continues based on host vehicle maneuvering jet firings commands determined by the TACM system. A preprogrammed approach vector profile continues to minimize thrusting in the direction of the target vehicle. The image mapping system also continues to update its data base during the maneuvering process and provides updated inputs into the TACM processor to improve alignment with the selected satellite axis; these inputs are integrated with distance information from the base mounted and the arm mounted laser sensors. Both of the prior inputs are compared to the evolved CAD motion model to confirm location of the satellite relative to the TACM and movement of the selection capture station (plane cut by TACM tip pads). When this envelope condition is attained, a signal is transmitted to the ground, requesting authorization to proceed to contact and capture.

2.3.4 Capture and Stabilization

This task includes all station keeping maneuvering and TACM movement required to establish contact and target vehicle capture. Capture is defined as having the TACM in controlled contact with the selected lateral surface of the target. See Figure 2-4.

Upon receipt of ground control authorization, the TACM arm proceeds further inward towards the target. The movement of the arm tip sections are synchronized with the inward/outward precessing motion of the target using the tip linear actuators. The overall plan is to maintain the main arm links stationary and only use the tip sections in a radial direction. The sensors located at each tip section provide distance information to the TACM spin table processor which performs the calculations to ensure that all arms contact the target at the same time and with the same force. Touch pad sensors located in each arm contact pad provide contact pressure information. Arm movements continue to support an even application of forces from all arms on the target. Control of the target is first performed by a programmed application of corrective pressure between the arms that diminishes the precession effect of the target; this takes into consideration the rigidity of the target surface, the location relative to the center of mass, and the corrective stability capability of the host vehicle thrusters. When the precession motion of the target vehicle has diminished such that the satellite is in pure spin, a braking force will be applied, using the host vehicle thrusters and controlled braking of the spin table. These forces are transferred to the satellite through the three arms. The despin operation is performed within the capability of the host vehicle thrusters to maintain stability and minimize pad slippage with the target. Upon reaching a stable (stationary) point, a status signal is transmitted to the ground, requesting authorization to apply rigidization contact forces.

2.3.5 Rigidization

This task includes all maneuvering and TACM movement required to establish/reestablish contact with the target vehicle at a location suitable for transport. Rigidization is defined as having the TACM in contact with the selected lateral surface of the target at an exerted pressure that allows safe transport of the target to another location. See Figure 2-4.

Upon receipt of ground control authorization, the TACM arms either change position along the lateral surface of the target or increase forces to a level that supports safe controlled transport. In the case where a change in location is warranted, contact pressure is released and the arms move to the new location. This operation is performed using the TACM arm movements only, if possible. If additional lateral movement is desired (i.e., to place the bottom of the target vehicle against "retention stops" or to grasp the target at the center of mass, the host vehicle thrusters will be used. The arm and base distance sensors support the change in location and coordinate symmetric contact application as required. Contact pad pressure information is also coordinated to ensure consistent and equal application of pressure to levels that support safe transport. Upon reaching that condition, a status signal is transmitted to the ground, requesting authorization to initiate transport.

2.3.6 Transport and Rendezvous with On-orbit Support System

Upon receipt of a signal from the ground, the TACM systems are shut down, except for those that maintain and transmit status information on rigidization pressure. The host vehicle propulsion system then propels the composite structure to rendezvous with the on-orbit support system for transfer of the captured object.

2.3.7 Hand-off to Support System

The host vehicle/TACM/captured satellite is stabilized at the transfer location.

To execute transfer of the object from the host vehicle/TACM to the local restraint system, the TACM arms are activated and move away from the object after the local interface has attached to the object. It is postulated that the local interface will constrain the object sufficient to enable safe maneuvering of the host vehicle away from the transfer point without disruptive influences of the thrusters.

3 Preliminary Systems Design - TACM Flight Demonstration Article

3.1 System Definition

The purpose of the capture system is to demonstrate capture of a target satellite in space under operational conditions of supervised autonomy and also to resolve technology issues which cannot be adequately verified by ground testing. The latter relate especially to space dynamics issues pertaining to controlled contact between the capture device and the target satellite and the level of supervised intelligence (automated approach, feature recognition and automated contact procedures) contained within the flight segment.

The proposed mission is to capture a communications class satellite of the type that could be spinning at a residual rate of 5 RPM along its major central axis and precessing at rates up to 5 RPM at a nutation angle of 5 degrees off the principal axis.

Aids are to be included on the capture mechanism system to support automated capture to the maximum extent feasible, lower ground operator work load, and mitigate the effects of time delay in the performance of the capture operations.

A shuttle based experiment and stand-alone booster/space propulsion platform are to be considered as possibilities for the host vehicle attachment.

A schematic showing the concept top level functional allocations between the TACM flight segment and interfacing elements is presented in Figure 3-1. The operator (located remotely at the ground control station) functions are limited to supervisory and administrative tasks such as authorizing phase initiation of major task phases, verifying that the remote vehicle has attained the objectives of specific phases of the mission using down-linked information, and override of safety procedures. The host vehicle is

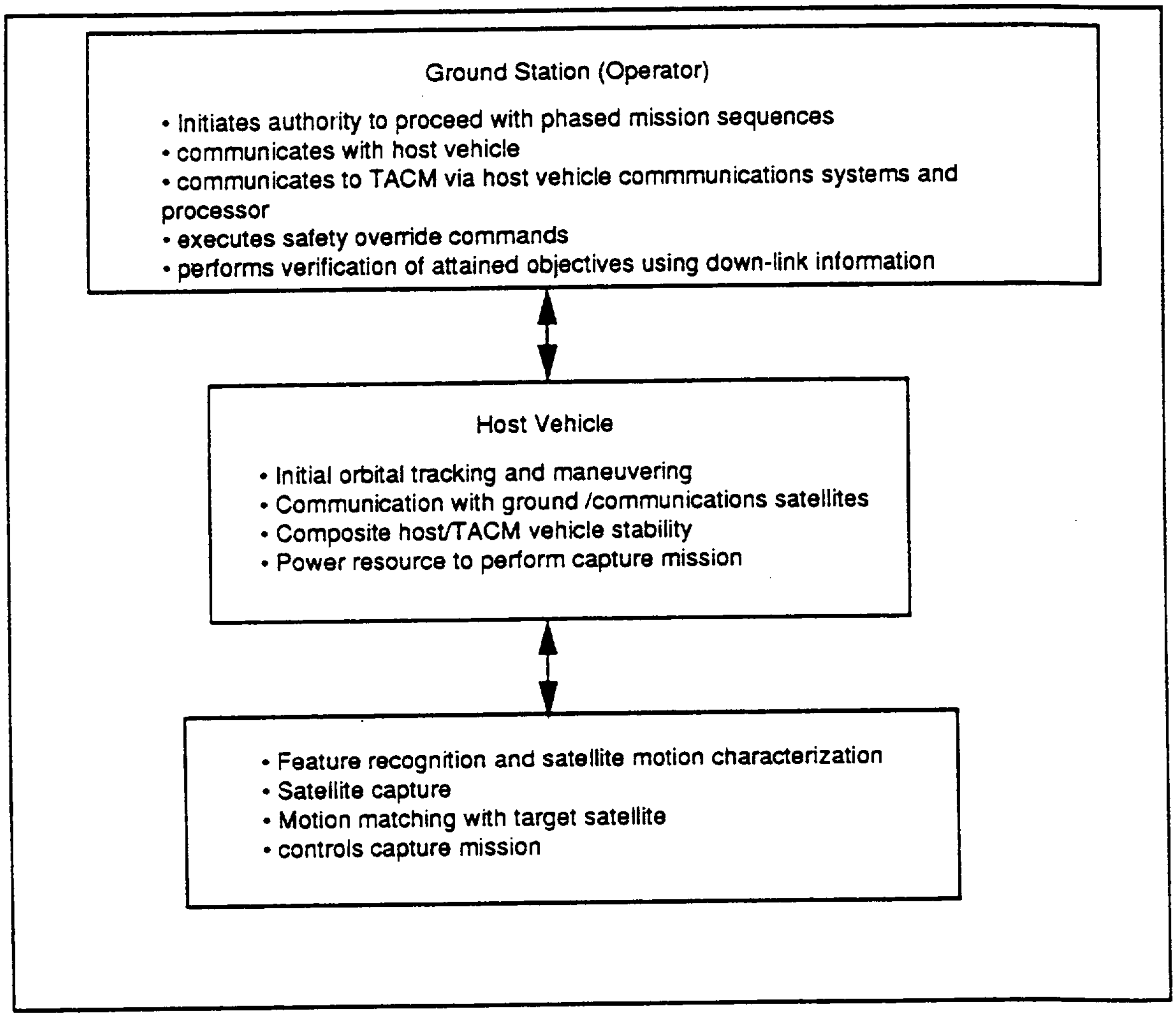


Fig. 3-1 Top Level System Functions and Interfaces

responsible for transport, providing TACM orientation, communication with the ground station and TACM, and power for all TACM operations. In this capacity, it also must provide a stable platform from which the capture operation is performed and subsequent transport of the captured object is accomplished. The TACM is responsible for all capture operation commands and capture movement required to bring the object under control for transport.

To accomplish these tasks, once the TACM image processors and laser sensors are within range, the TACM assumes active control of the capture mission. The computers located on the TACM provide orientation commands to the host vehicle and analyze data to determine the location and motion state of the object.

A block diagram of the elements comprising the TACM flight demonstration system is presented in Figure 3-2. The structure is fastened to the host vehicle using a bolt pattern; this facilitates direct transfer of loads to the host vehicle. Should load damping of impact loads be required, introduction of dampers in the arm sections at a more mature point in the design can be considered. The spin table is mounted to the TACM structure via a large bearing assembly. Power and data cross the rotating interface using slip rings. The spin table provides the structural base for the three two-link capture arms which each have passive compliant pads to facilitate the capture operation. Each pad assembly also has a smaller, fast acting linear actuator to support minimizing contact loads. The image processor which plays a major role in directing the path of capture is mounted on the spin table, collocated with a laser sensor provides target distance information.

3.2 TACM Concept Description

The description presented in this section presents a concept configuration to perform the capture mission. Component sizing and performance values were based on postulated mission parameters, derived requirements and lessons learned from the previous simulations performed by Grumman, and

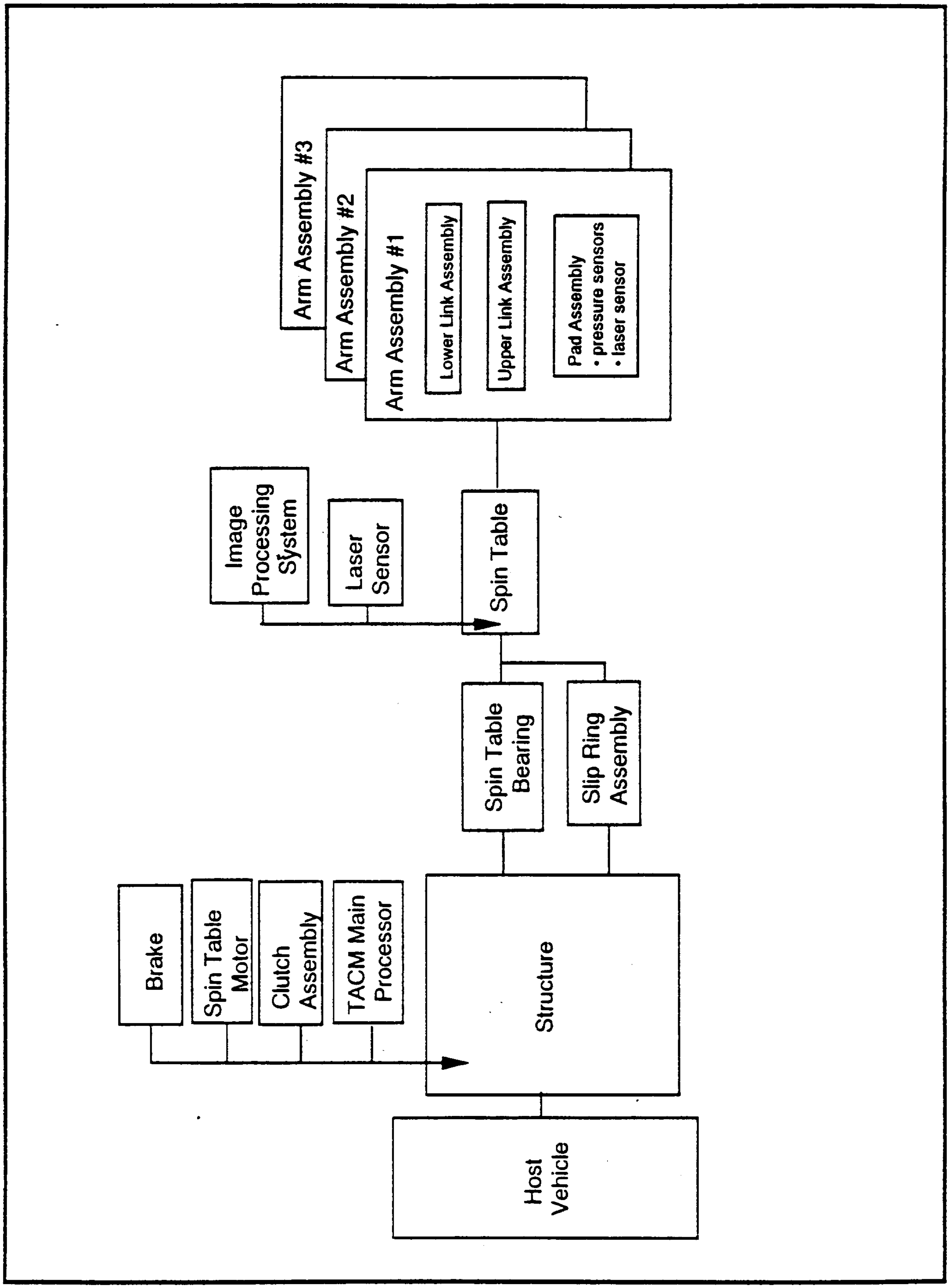


Fig. 3-2 Block Diagram of Major TACM Elements

first order calculations which provide concept system level sizing information for component selection.

Additional design constraints to account for launch loads and specific vehicle safety factors have not been included nor addressed.

Component selection was made based on estimated performance requirements and experience resulting from the many series of satellite capture simulations performed in Grumman's Large Amplitude Space Simulator. Product selection was guided by available performance specifications of commercial equipment, since directly applicable flight equipment is not available. Specification information for components was requested on the basis of estimated flight use where possible.

Figure 1-4 shows a sketch of the concept mechanism. To perform the mission, the mechanism must be attached to a stable platform that can maintain position while the TACM spins up to match motion with a target satellite. The composite vehicle must react to controlled contact loads and be able to despin an object in space. It is composed of three two-link arms attached to a spin table. The TACM is solidly attached to a host vehicle. For the postulated mission case, a mechanism with three 12 foot arms is required. The arms provide a maximum grasp diameter of about 160 inches.

Each arm is comprised of two links, each controlled by a linear actuator and a pad assembly which also has a smaller linear actuator. The two arms provide rough positioning, with final capture movement being provided by the pad assembly actuator. The three arms are positioned 120 degrees apart, attached to a spin table. The latter provides spin matching between the capture vehicle and target satellite.

Vehicle positioning, motion matching and arm positioning is aided by an integrated control system composed of sensors, an image recognition system, and inputs to the TACM spin table motor drive, the three arm actuators and host vehicle propulsion system. Only supervisory inputs are anticipated from the ground station during the capture operation.

The following sections describe each subsystem or major component as to its intended function, basis for sizing, and significant parameters for mission performance.

3.2.1 Structure

The structure is the load bearing path that transmits forces to the host vehicle from the TACM. It is envisioned to be an open aluminum frame structure with exterior environmental control skins. The host vehicle, during mission operations, would be expected to counter these forces using reaction control jets to provide a stable TACM platform. The structure will contain mounting provisions for the main computer processor and elements of the spin table assembly which include the motor and other rotary support equipment. The spin table bearing assembly will be mounted to the structure surface, providing the load path from the spin table and its attached arm.

3.2.2 Spin Table Assembly

The purpose of the spin table assembly is to provide rotational motion for the attached arms to position themselves relative to the target satellite. It contains the following major subassemblies:

- motor and reduction gear
- the spin table shaft and drive assembly
- slip brake and coupling
- slip ring

It also provides mounting area for the camera and 2-D image processor, base mounted laser positioning system, the three capture arm assemblies and associated control and instrumentation wiring.

Motor

A stipulated constraint for the motor is to run off 28 VDC regulated power supply. A brushless design was selected for the baseline design. Brushless motors run better above a minimum 500 RPM. To prevent undesirable moment disturbance effects of the host vehicle (and minimize RCS thruster use) the motor was located in line with the principle TACM spin axis.

The sizing parameter for the motor was the moment of inertia of the TACM components. Based on the preliminary requirement to provide a variable rotation speed capability at a maximum nominal imposed 10 RPM output rotation rate, a speed reducer was included. It was decided to increase the speed reduction rate to 100:1 so that increased capability for small variances was available. A TACM "spin-up" configuration where the arms were spread at their widest point was used to size the motor; this places the arm mass furthest away form the centerline. The merits of including incremental rotational movement capability (step movements) to accommodate specific capture strategies (which would be developed as part of detail design) will be assessed later.

3.2.3 Capture Arm Assembly

3.2.3.1 Mechanism Structure

The frame will probably be of extruded and fastened aluminum; trades focused on using alternative materials such as composites and special strength materials should be considered as part of normal design process.

3.2.3.2 Actuators and Arm Assembly Structure

For the concept 12 foot arm design, three actuators will be required per arm. A summary of the concept specifications are summarized in Figure 3-3. The allowable loads given in the table are for the commercial equipment and are within the calculated mechanism arm load conditions during spin up.

Link	Throw (inches)	Rated load (pounds)	Power Reqm't (amps @ 28 VDC)	Speed of Movement (inches per second)	Max. Dynamic Load (lbs.)
lower	22 inches	1000	18	2.5 at no load; low speed at load	500 tensile
upper	34 inches	1000	33	2.5 at no load; low speed at load	1000 compression
tip	20 inches	75 (while moving)*	5	10 in/sec at load	75 tensile
		* should be able to take higher loads when bottomed against stops			

Figure 3-3 Concept Actuator Specifications

The loads imposed on the arms and the actuators during capture and despin should be regulated based on a selected control strategy which also addressed the capabilities of the host ACS. Contact dynamics analysis must be performed to determine anticipated loads that could be experienced during capture and despin conditions to verify that the design is realistic and that the reaction control jets selected are able to provide stability during the postulated capture mission operation.

The actuators for the two major arms links can be of the acme screw design, but ball screw designs could be considered. Their function will be to provide initial positioning and exert the loads on the satellite required for final stabilization and transport. Although the acme screw design is lower in efficiency, it is self locking and cannot be back driven by the load. These links are driven to the envelope position and should not move during the time when the tip actuator follows movement of the satellite surface to perform the capture operation. The speed requirement of these actuators are nominal and should not require special designs. The loads identified in Fig. 3-3 represent an estimate of the actuator loads resulting from holding the target satellite and preventing it from "shifting" along the major thrust axis of the host vehicle.

The tip actuator's primary use is to exert the necessary force to contact the satellite with minimum disturbance torque and then slowly, according to a preset control sequence, reduce the precession rate of the captured satellite until it is in pure spin. The time required to perform this operation will be based on parameters such satellite surface strength, location of contact relative to the satellite center of mass, the satellite moment of inertia, et al. The tip actuator is required to move (in a radial direction) at a faster rate than the local precessing satellite surface changes its effective local radius. A ball screw design generally is associated with this requirement. After contact with the satellite has been made, small force increments will be applied to decrease the precession rate. Once the precession effects are minimized by controlled force reaction, each tip actuator shaft is slowly retracted while the major links are moved to maintain constant pressure at the satellite surface.

The process will continue until the tip actuator is fully retracted (against its stops) and further pressure increases can be exerted using the main link actuators.

Actuator position is required as an input to the control schema, requiring an encoder at each actuator motor. Limit switches would also be part of the design.

3.2.3.3 Capture Pads

It is very important to contact the satellite with as much surface area as possible to reduce the average pressure load on the satellite surface. Our concept is a circular series of compliant cylinders joined to the pad plate. This approach (See Fig. 3-4) uses the capability of the cylinders to deform to reduce impact loads. The cylinders could each be made of a spring, encased in protective material or a deformable rubber that has resiliency. The material used must withstand the space environment and booster safety standards.

The level of load absorption required will be determined by impact contact dynamics modeling and assessing the flexibility of the structure and capability of the reaction control jets to counter the imbalance load conditions. The need for additional measures such as a tip actuator damper assist or a spherical bearing at the pad-actuator joint will evolve from this analysis.

The linear actuator located in each pad assembly allows travel to either increase the pressure force or decrease it accordingly so consistent forces using all three arms support the planned capture control logic. Sensors contained in the top surface of each pad cylinder generate force information that is used to command actuator position and direction to maintain desired levels of arm load conditions. Depending on the linear and repeatability characteristics of the cylinder assemblies, the measurements could be placed at the base of the cylinder, thus avoiding the potential for abrasion. Some

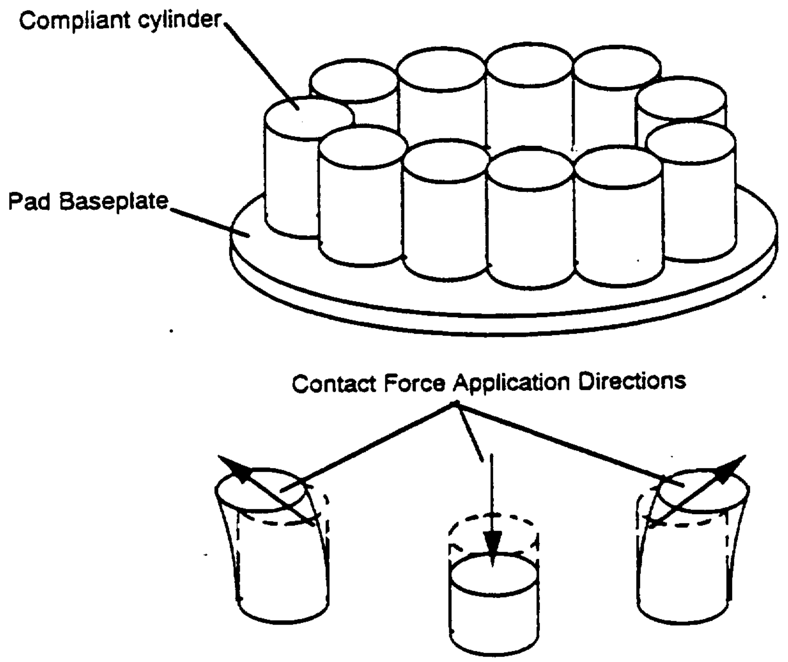


Fig. 3-4 Capture pad configuration

measurements are still required at the top surface to provide indications of target satellite contact load direction.

3.2.3.4 Sensors

Pressure sensors, of a type using polymeric piezoelectric films are used in our concept to provide pad surface pressure data on impact and subsequent loading conditions. This film material transforms a mechanical force to an electrical response. According to vendor information (Reference 9) the material is pliant, tough and lightweight and has piezoelectric sensitivities that can be used in this application. We envision that multiple sensors will be located on each pad. These can be then averaged to generate pressure information or used absolutely for impact load avoidance measures. The contact force data would be used to equalize contact forces among all arms and support contact force logic that controls the arm movements to ensure that the resulting loads remain within the design basis of the TACM.

A laser ranging system is deployed within each pad to transmit the local radial distance to the satellite. The system is envisioned to comprise a diode laser with a scanner and optical detector as depicted on Fig. 3-5. The accuracy of this system should approach about 0.125 inches in the near field with degraded resolution in the far field. Range information should be updated at a rate in the millisecond time frame. Based on discussion with laser system companies,[10] commercial type hardware can be made available to support our application They propose a small rectangular box with two 1" optics on one face and a power/serial data connection on the opposite face that emits an eye safe laser beam at 851 nm from one lens and receives a reflected optical signal through the other lens. The expected change in radial direction of the satellite in the postulated mission case is 0.5 inches per second.

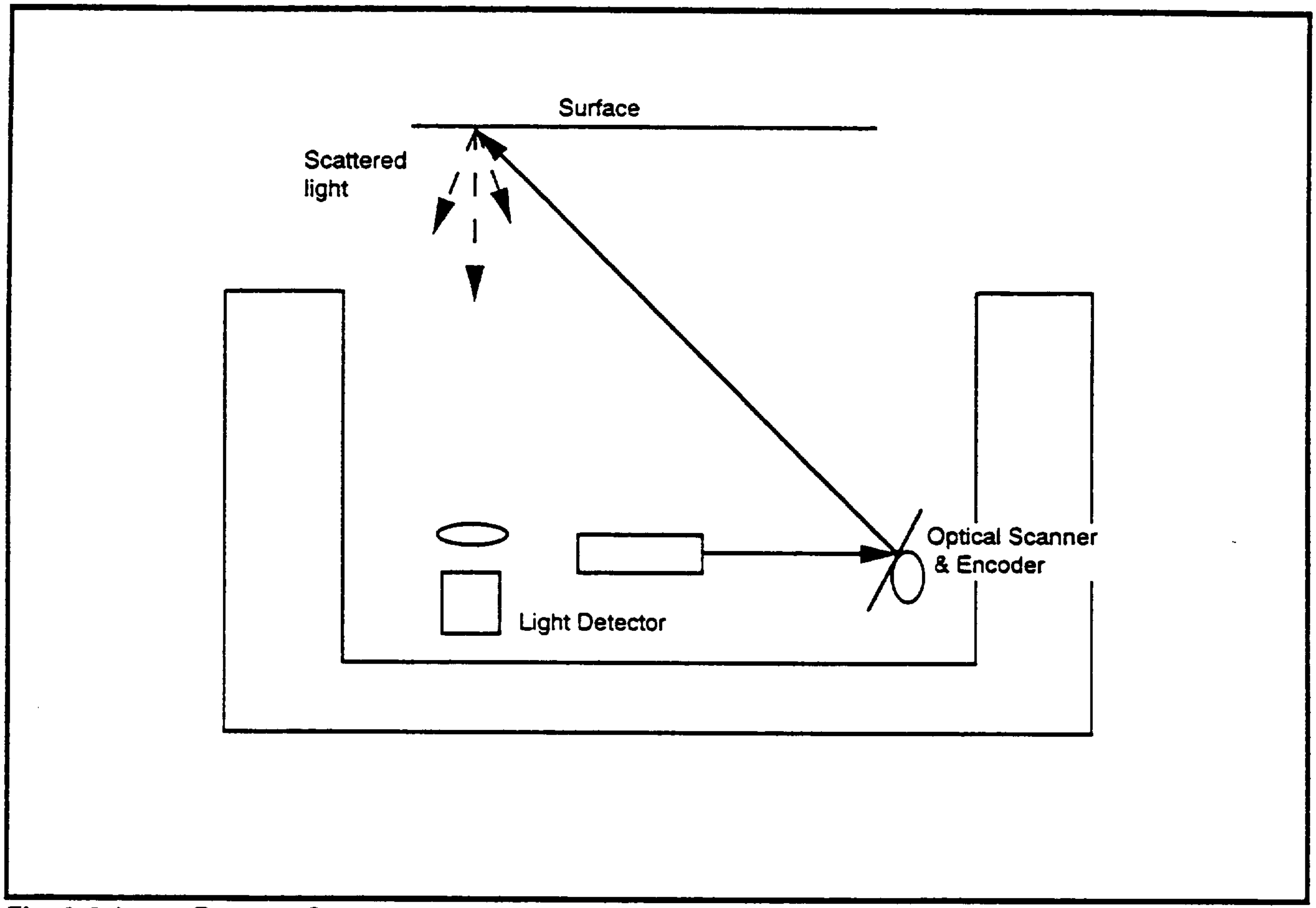


Fig. 3-5 Laser Ranging System

3.2.4 Target Recognition System

3.2.4.1 Approach

The objective is to devise a method to identify and completely model the motion of a known, uncooperative satellite in space, and to use this information to capture that satellite. The postulated motion conditions that the object could have includes spin and precession. The postulated configuration is that of a cylindrical communications satellite.

The sensing requirements of the satellite capture problem are based on the need to do (1) satellite identification, (2) maneuver for capture, and (3) perform capture. While the most generic recognition problem requires a system that will try to identify an unknown object, the approach postulated for the present study for (1) is based on the detection of key target satellite features for identification purposes such as movement, envelope, shading/color, special markings, general shape, and landmarks e.g. solar panels or antennae or unique and easily detectable shapes. For (2), our approach is to first determine the motion characteristics of the satellite from the processed image information above. After establishing and confirming the motion characteristics with further image information we establish key features that are readily detectable and allow faster processing of selected local features during the maneuvering and approach process. Part (3) includes the maneuvering and final approach associated with the capture process after the relative motion state between the two vehicles is determined and can be predicted using the developed model.

Existing space application work has mostly been directed at recognition of specific feature targets (decals) by imagers (Reference 5, 6). The target satellite, in the former cases were assumed to be stationary in known locations and orientations. Our thrust does not assume such aids are available on the satellite and seeks to analyze and compare images and time-sequenced patterns to CAD database and/or other intelligence information to verify identification and predict movement patterns of object surfaces and determine satellite orientation. Selected control strategies will then be used to maneuver the chase vehicle and the attached capture kit into an orientation best suited for performing the capture operation. The latter effort will be discussed further in section 3.2.5.

As a baseline for performing the recognition task we are selecting two sensory elements which are to work in tandem. We are selecting a 2-D CCD camera system augmented with a laser distance measurement system. The image data are analyzed by an onboard computer processing system. The resulting information is compared against CAD database information towards attaining identification and satellite movement predictions. A laser ranging system, collocated at the base of the spin table with the camera, provides primary depth data; this sensor is used as an approach sensor during the capture phase of the mission. Considerable development has been made on auto focus lenses that enable imaging during times of direct sun; support lighting will provide ample lighting in times of total darkness. As technology advances are made, component parts of the imaging system can be upgraded and modified (e.g. 2-D CCD image processing to 3-D CCD image processing and perhaps a total replacement by an alternative 3-D laser system); the parameter values defined in this study (i.e. weight, power, data processing throughput) would still be meaningful.

3.2.4.2 Description of CCD Imager and Processing System

The distance of the object from the camera varies from tens of meters during satellite identification to under a meter when closing in for the capture. Hence the camera must be equipped with zoom lenses. Also as lighting condition is variable, an auto-iris mechanism must also be provided. To provide sufficient resolution for image processing, the size of the image array should be 256 x 256 or larger.

The image processing methodology in terms of the capture scenario elements is presented in Figures 3-6 through 3-9. In the 'identify' stage (Figure 3-7), the edges and segments are obtained from the image.

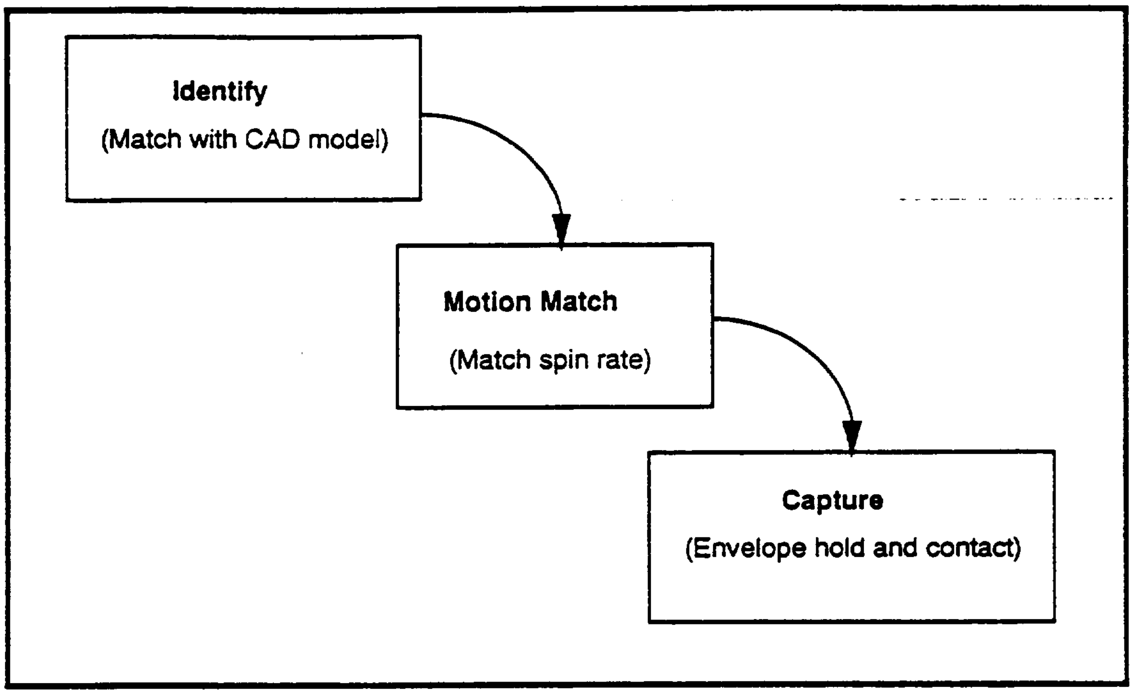


Fig. 3-6 Image Processing Methodology Applied to Capture Scenario Tasks

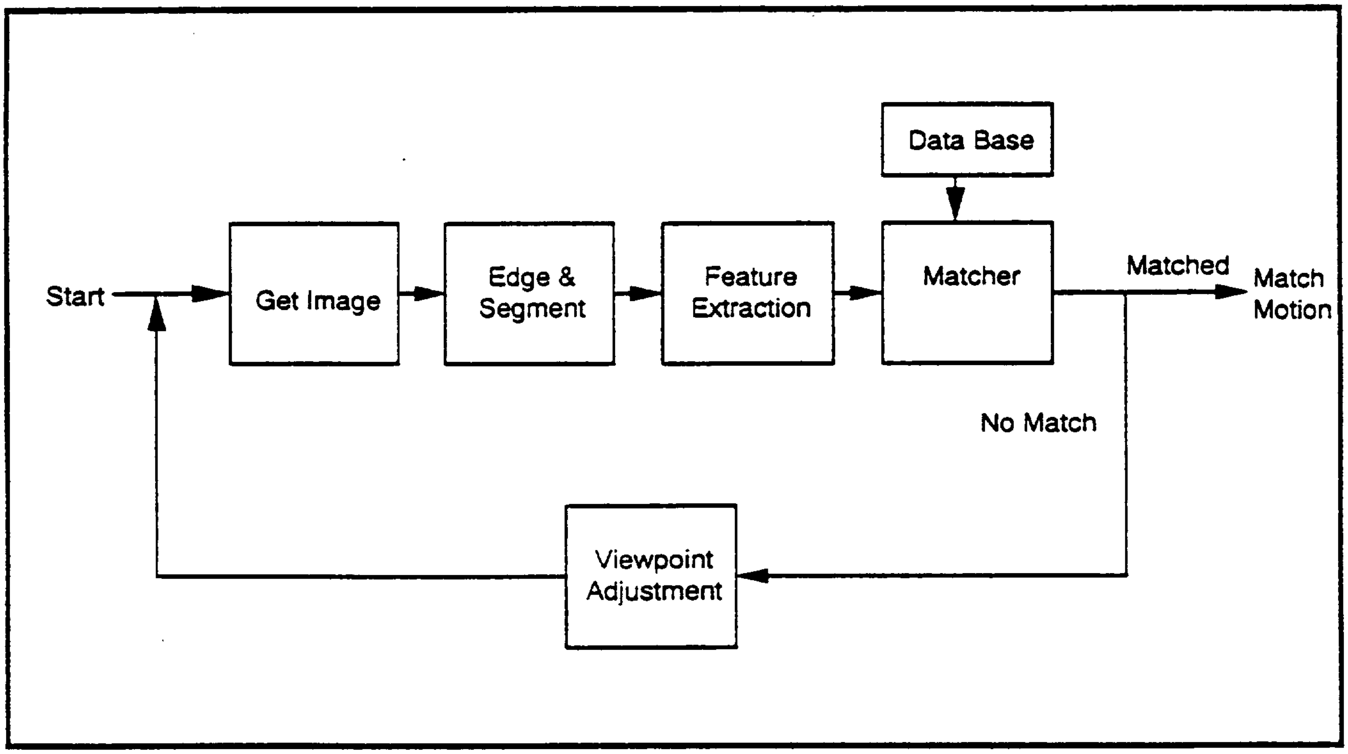


Fig. 3-7 'Identify' Portion of Image Processing Methodology

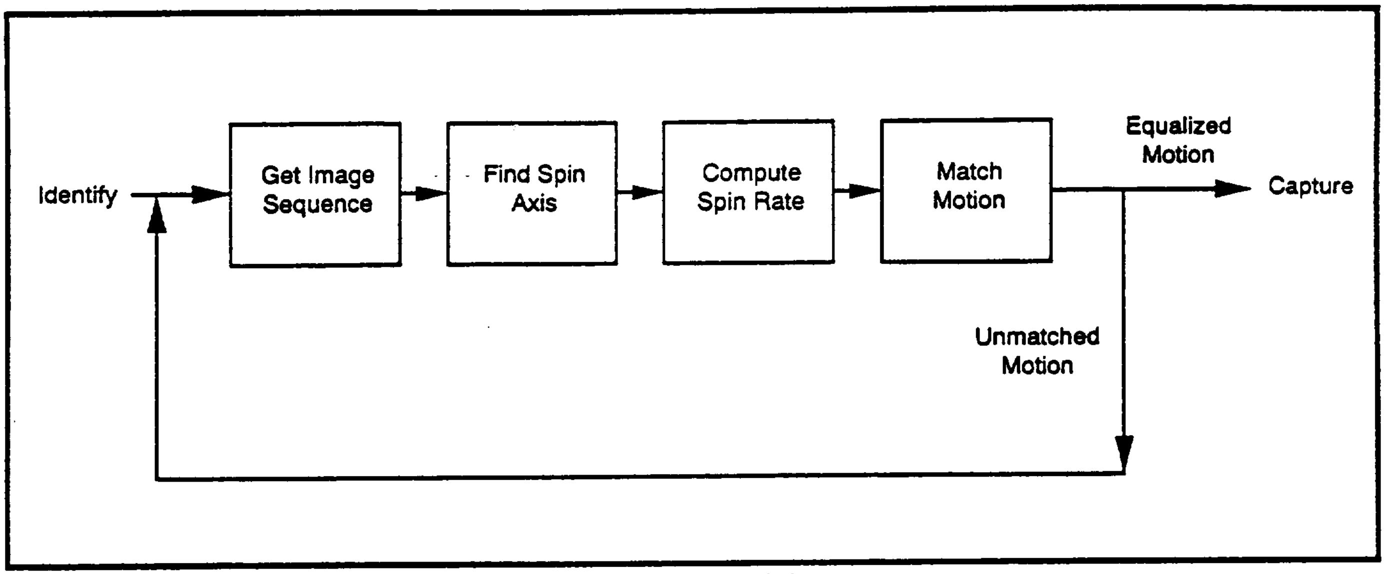


Fig. 3-8 Motion Match Portion of Image Processing Methodology

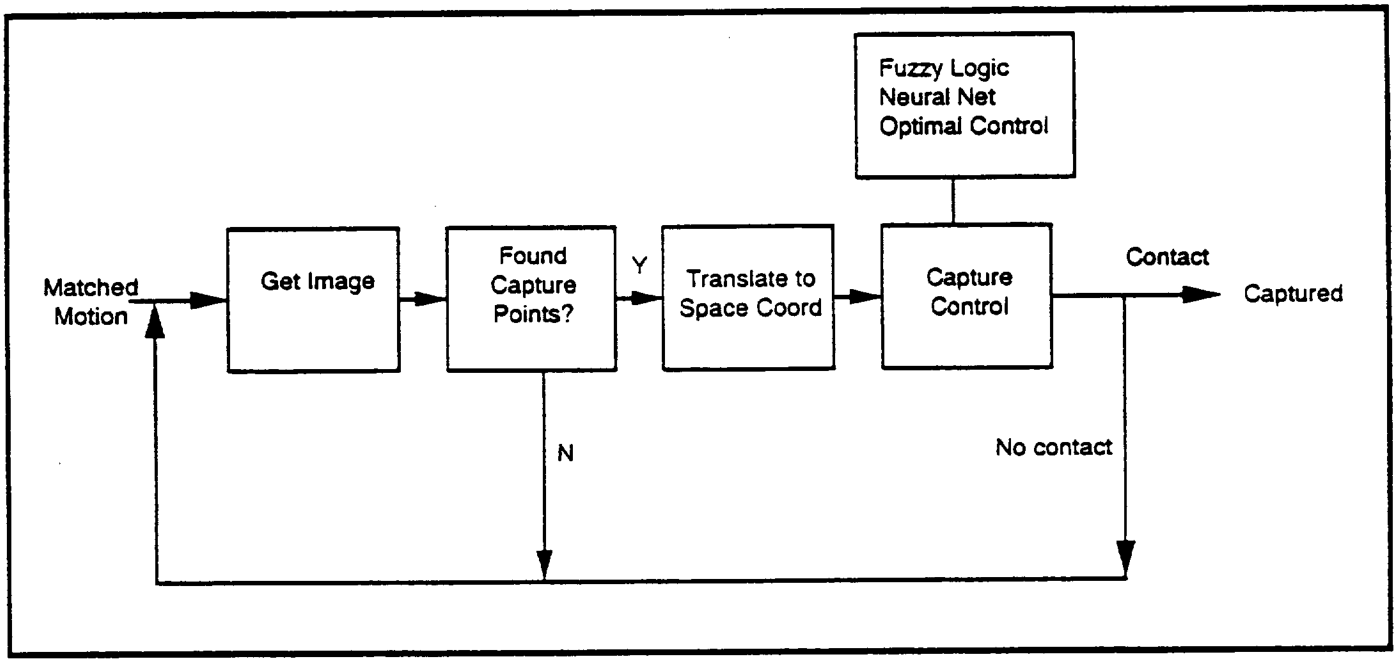


Fig. 3-9 Capture Portion of Image Processing Methodology

Relevant image features such as object boundary and markings are derived from the edges and segments. The clarity of the image data, taken at an instant of time, is not effected by the continuing motion of the target since the data is received almost instantaneously compared to the motion of the target. These features are matched against predicted image features obtained from the model stored in the data base. These predicted image features are 2-D projections of surface and other features from the 3-D based CAD data. If there is no match, the viewpoint of the TACM is adjusted to get better image features. The image processing system provides inputs to the TACM main computer which provides position specifications to the control system of the host vehicle to move around the target in a prescribed manner. The continuing adjustments are driven by the evolving scenario data base file. When the object in the image is matched to a specific model in the data base, the next image processing function to be performed is motion matching (Fig. 3-8). The data captured by the imaging system is saved in a data file and is used in a model-based fashion to predict the motion state. The motion state possibilities are also predicted from inertial information. Once both the object shape and movement are determined in space coordinates, the TACM can start orienting itself along a desirable capture vector.

To match the motion, the TACM is first oriented along a desirable approach vector. A sequence of images are obtained from the camera. Confirmation that the TACM is along the required approach vector is determined by comparison of the image views with the predicted data base view. Again the TACM is tracking a moving object where the image data is taken at an instant of time.

The instantaneous TACM approach vector is determined by tracking the motion of the silhouette of the object. Then the deviation of the actual approach vector and the desired vector is calculated and the TACM moves to the improved orientation.

After attaining the desired orientation, motion matching is then attempted by using information derived from image data sequences (Fig. 3-8). This is done through a combination of predicting and comparing the view of the object as the TACM spin table rotates to the desired rate. This rotation matching process continues until the actual image view matches the predicted data base view. We will investigate the possibility of using an extended Kalman filter to estimate the vehicle parameters.

When motion matching is completed, object capture is attempted. In this mode, the image processing system supports tracking of the capture points using the developed data base and feeds back their position and velocity to the control system. The TACM proceeds along the desired approach vector until the selected capture station is reached; data to determine this location is provided by both the image processing images, the arm and base mounted laser ranging sensors and their assessment with data base files. The arm mounted laser ranging system provides distance data to the immediate target surface. The control system moves the tip actuator arms to first follow the local target surface and then make contact. The pads of the arms are moved into position to grasp the object, using fuzzy logic or neural net optimal control techniques; see Fig. 3-9.

3.2.4.3 Base Laser System

A similar laser distance measurement system is used. The system is collocated on the spin table base. The resolution of the laser system must match that of the 2-D CCD camera. For the z-dimension, the resolution should also match that of the x and y dimensions of the 2-D CCD camera. The critical values for these resolutions are determined by the accuracy required for determining the cone axis, cone angle, and spin rate.

3.2.4.4 Description of Model Data Base

The model data base contains the CAD data necessary for satellite identification. This includes the 3-D information for predicting the attitude of the satellite. This prediction is used to aid satellite identification and motion and trajectory estimation. For example, the projection of the satellite's outline onto a 2-D plane can be used to match against the image or to "fill-in" for missing edges in the image. Thus the satellite's outline in the image need not be "perfect." During the maneuver for capture and capture itself, the model can be used to predict the visible shape of the satellite, its substructures, or markings, in the image from the view-point of the camera.

3.2.4.5 Required algorithms

The algorithms required include those for low level image processing (e.g. edge detectors, boundary trackers), blob tracking, motion detection, and model matching.

3.2.4.6 Description of Lighting

Our concept provides lighting using tungsten halogen lamps with a fixed reflector geometry. The definition of wattage and field of illumination should support the camera lens requirements.

3.2.4.7 Description of Laser Mapper (alternative - not included in baseline)

Like the CCD system above, the laser mapper system is to generate a picture of the satellite albeit in this case a 3-D representation. If both were used on the same mission, using the 2-D CCD camera system as the primary imaging system, the laser would serve as a backup when the lighting condition is not good enough for proper imaging and take over the ranging function. The 2-D resolution (x-y plane) of the laser mapper must match that of the 2-D CCD camera. For the z-dimension, the resolution should also match that of the x and y dimensions. The critical values for these resolutions are determined by the accuracy required for determining the cone axis, cone angle, and spin rate.

3-D object sensing systems that use video camera, structured light illumination, and high-speed computation to measure points and surfaces in a stationary and moving three dimensional scene are under development.

One system[11] is said to be able to measure and process a full scene of about 50,000 points with very high precision in about 0.05 seconds. All of the measurement data may be acquired as fast as 1/10,000 seconds which allows the sensor to make nearly instantaneous measurements of objects in motion. Measurement accuracy is about 1/2000 of the field of view; thus with a 4 inch field of view, the system can measure the location of objects in a scene to an absolute accuracy (one standard deviation) of about 0.002 inches.

This system has no moving parts. A structured light pattern in the form of a fan of multiple light planes is generated by a solid-state laser and optics. Laser stripes generated by the reflection of the structured light pattern off of the 3D scene are measured by the video system then passed to a high speed image processor. The image processor locates all stripes in the image and calculates their 3-D coordinates in near real-time using triangulation.

3.2.5 Control System Definition

3.2.5.1 Approach Methodology for Capture

The primary strategy for approaching the target satellite is to determine a vector relative to the target which minimizes the satellite surface motion relative to each of the three TACM pads when the TACM is at the desired spin rate. A top-level capture mission control scheme is presented by Fig. 3-10. It shows the major elements that support the controlled capture mission under the requirement that the TACM perform the mission under conditions of supervised autonomy.

The optimum approach vector for the case of pure spin around the axis of symmetry is to align the TACM spin axis with the satellite spin axis. Spinning the TACM to match the satellite spin rate produces zero relative motion for the satellite surface point directly below each pad with respect to the pad frame of reference. Achieving this condition, insures that the contact forces between each pad and its respective satellite surface contact

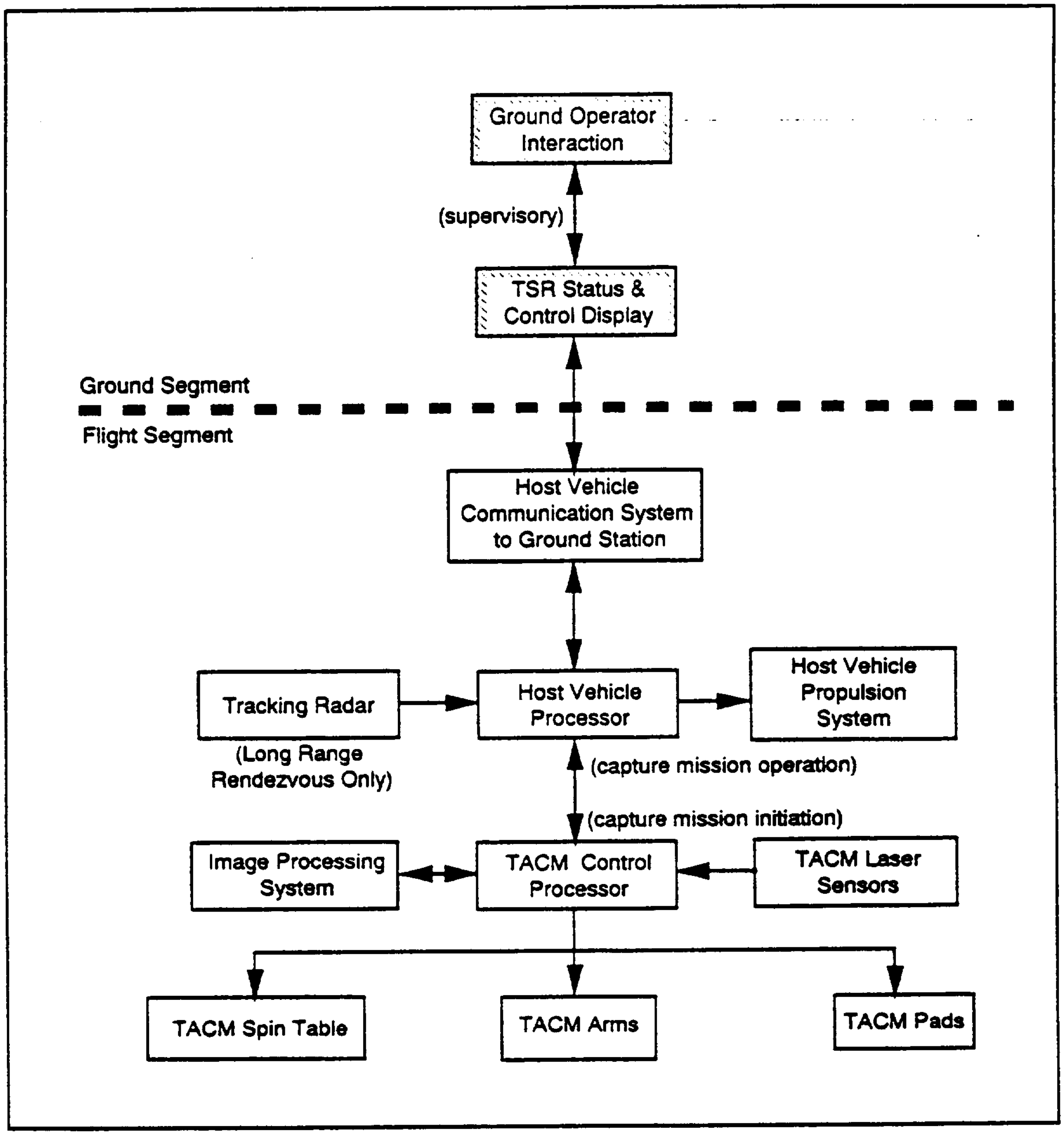


Fig. 3-10 TACM System Control Logic

point will be collinear with the pad actuator axis (minimal contact side loads).

The correct approach vector for a target satellite motion which includes precession is not quite as clear. A non-real-time computer simulation was developed to help evaluate and analyze this case. The simulation was written using the Advanced Control and Simulation Language (ACSL) running on a SUN SPARC Station computer. The user can specify target dimensions, mass properties, spin rate about the axis of symmetry and the nutation angle. The TACM position and attitude (pitch angle), relative to the target, and spin rate can also be specified. The simulation calculates and stores the initial point of intersection along the sight line of each TACM pad to the satellite surface at the start of the simulation. The three points are tracked with respect to their pads to determine relative motion.

The primary coordinate system used for the kinematics analysis of the target/TACM is presented in Fig. 3-11. Target body coordinates are chosen as the principal axes of a typical cylindrical satellite, like Intelsat 6, with the "z" axis aligned with the target axis of symmetry (spin axis). The TACM body axis is centered on the spin axis platform with "z" axis aligned on the spin axis. A TACM spin axis coordinate system is defined which shares the same origin as the TACM body system but rotates with the TACM. A local pad coordinate system is defined for each of the three linear locations. The positive "y" axis is collinear with the pad linear actuator. The other coordinate directions for each of the systems are as shown and obey the "right hand "rule. An inertial system is defined as shown. Target and TACM orientation are defined relative to inertial coordinates.

Initial simulation work shows that pitching the TACM with respect to the target satellite reduces the magnitude of the surface motion that each pad "sees". While the ultimate approach would be to exactly emulate the motion of the satellite with the TACM before attempting capture, exact motion matching may not be attained. Residual momentum impact forces may still have to be accommodated during the capture operation. The following

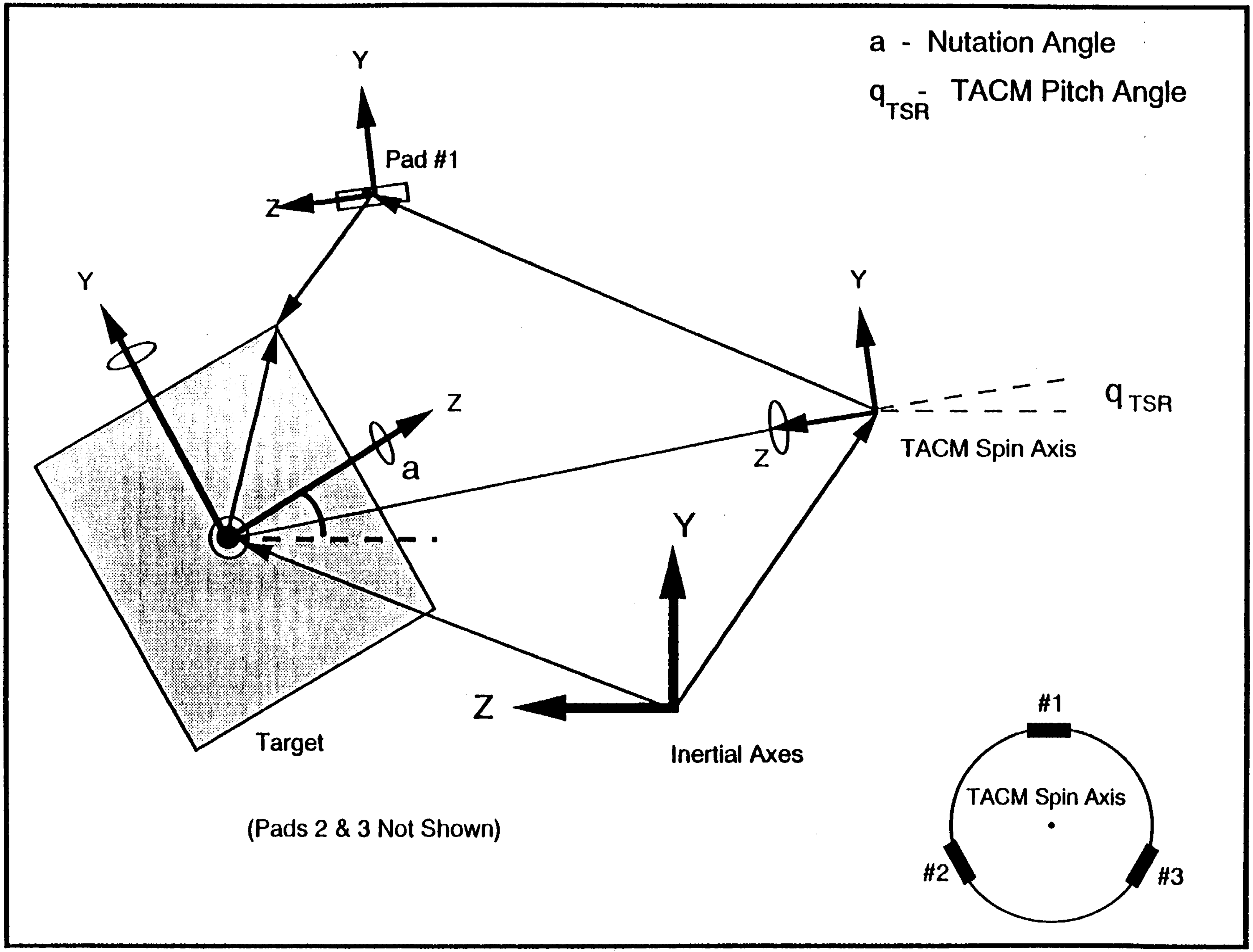


Fig. 3-11 Coordinate System Used for Target/TACM Kinematic Analysis

paragraphs discuss the case where some relative motion would still be present during capture. The purpose of the following discussion is to define an approach for problem analysis, thereby identifying realistic requirements for the TACM design.

Figure 3-12 presents the relative motion of a point on the satellite along the line of sight below a pad when the target is in pure spin. The distance and line of sight angle between the capture pad and surface of the satellite remains unchanged. The angle of the plane, which contains all three capture mechanism pads would be normal to the spin axis of the satellite and TACM.

Adding a precessing motion to the satellite spin condition, causes the point on the satellite to wander back and forth and also towards and away from the pad. This is shown by a pad line of sight relative motion and distance trace in Figure 3-13. This point was selected to not pass through the center of mass.

Changing the approach angle of the mechanism to the satellite to approximately equal to the nutation angle decreases the amplitude of the changes as shown by Figure 3-14. We have now approximately emulated the rotation of the satellite using only the spin table for motion and the host for attitude changes. Radial changes ("Y" direction) are tracked using an active pad actuator system. The remaining residual motions are handled using a TACM control strategy that includes arm and pad compliance, host vehicle RCS jet reactive forces, and TACM structural flexibility. Assuming that the capture plane cuts through the center of mass of the satellite results in an even more improved initial capture condition (Figure 3-15), but may not be as favorable for applying forces to despin the target.

Assuming we capture at the position typically described by motions of Figure 3-14, we propose that the approach be to minimize contact loads during capture. The momentum transfer in the radial direction (Y-axis) could be reduced and controlled within planned limits by moving the pad

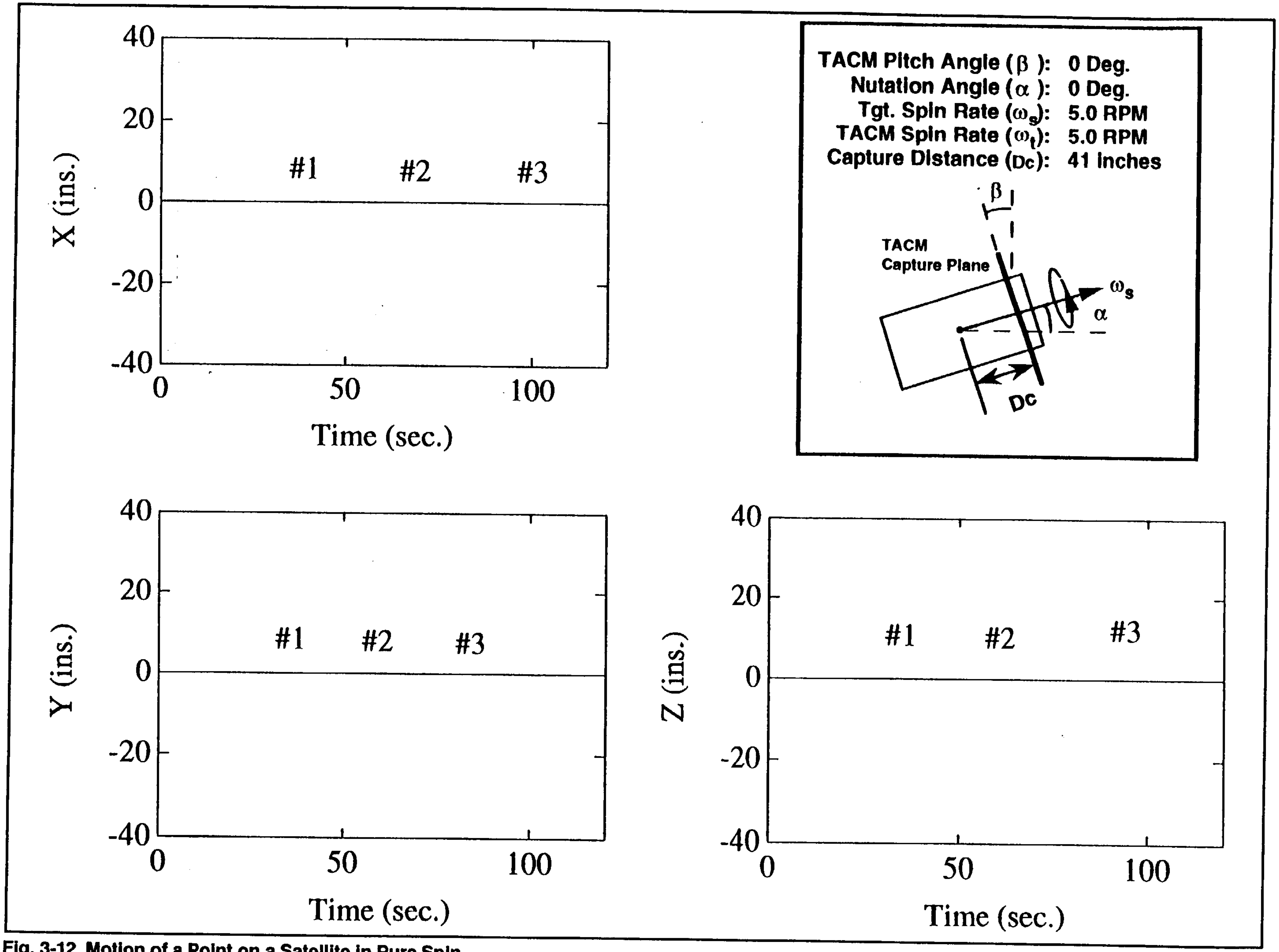


Fig. 3-12 Motion of a Point on a Satellite in Pure Spin

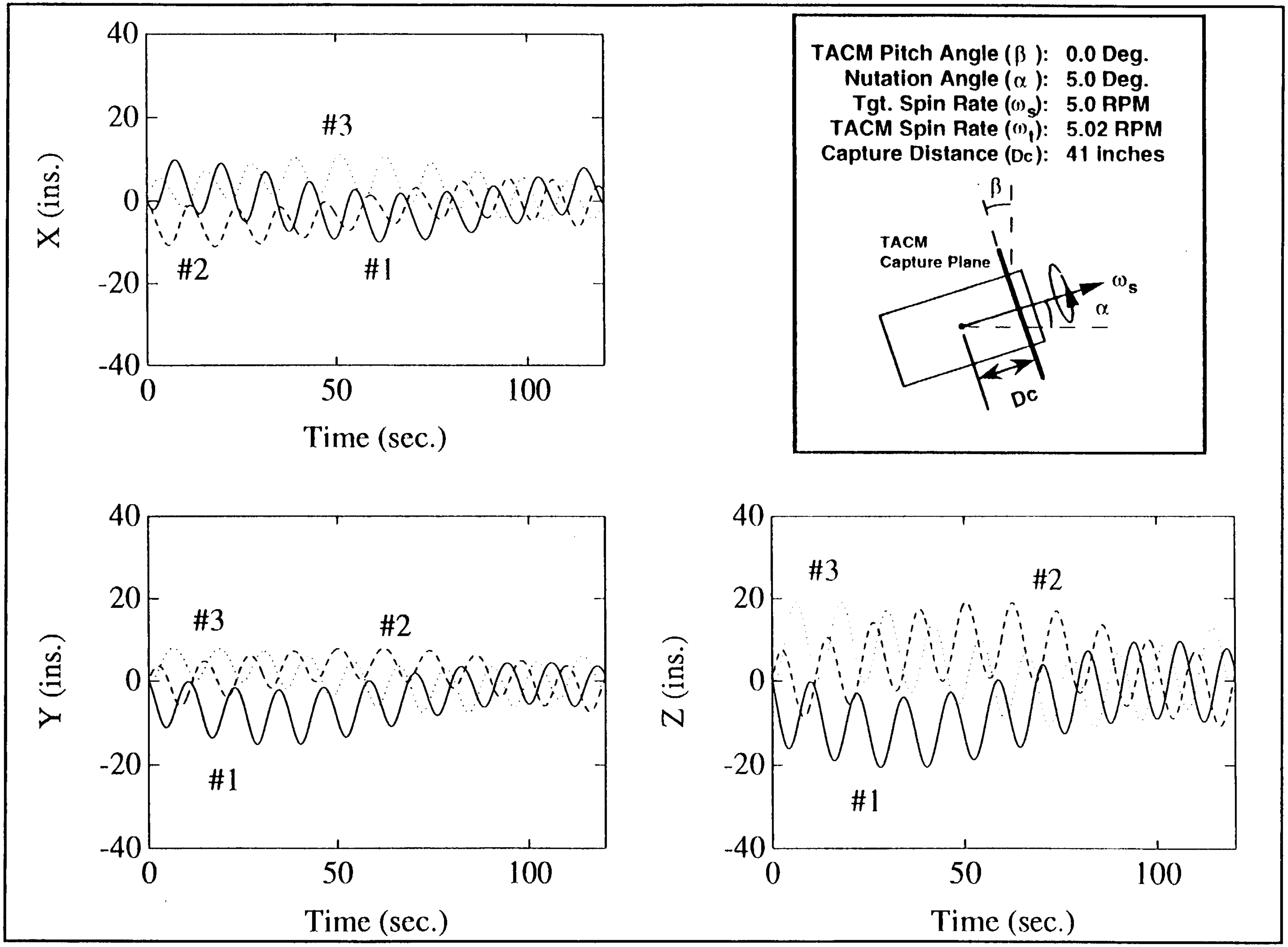


Fig. 3-13 Motion of a Point on a Precessing Satellite (Along a Selected Line of Sight; Pitch Angle = 0)

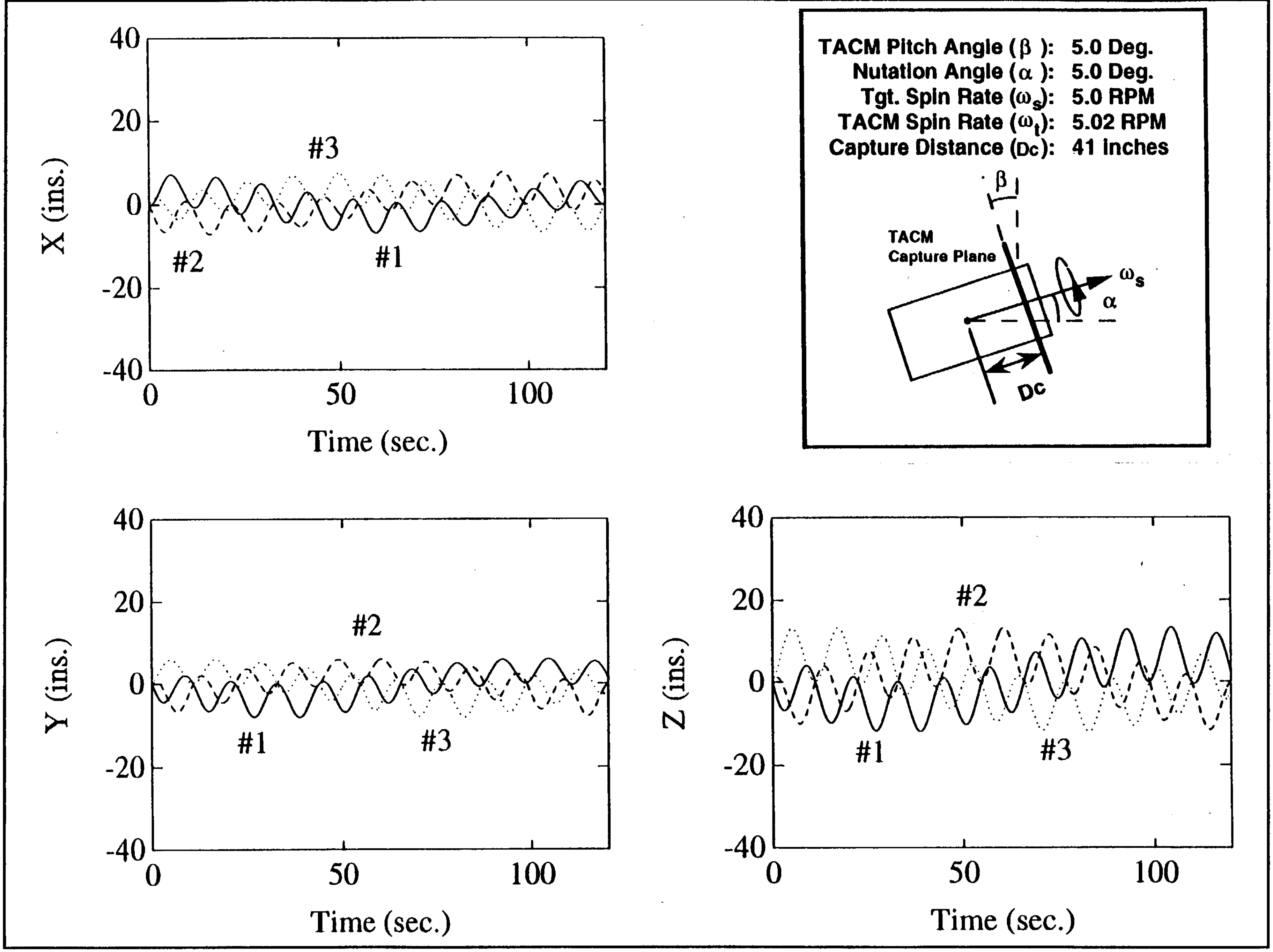


Fig. 3-14 Motion of a Point on a Precessing Satellite (Along a Selected Line of Sight; Pitch Angle = Nutation Angle)

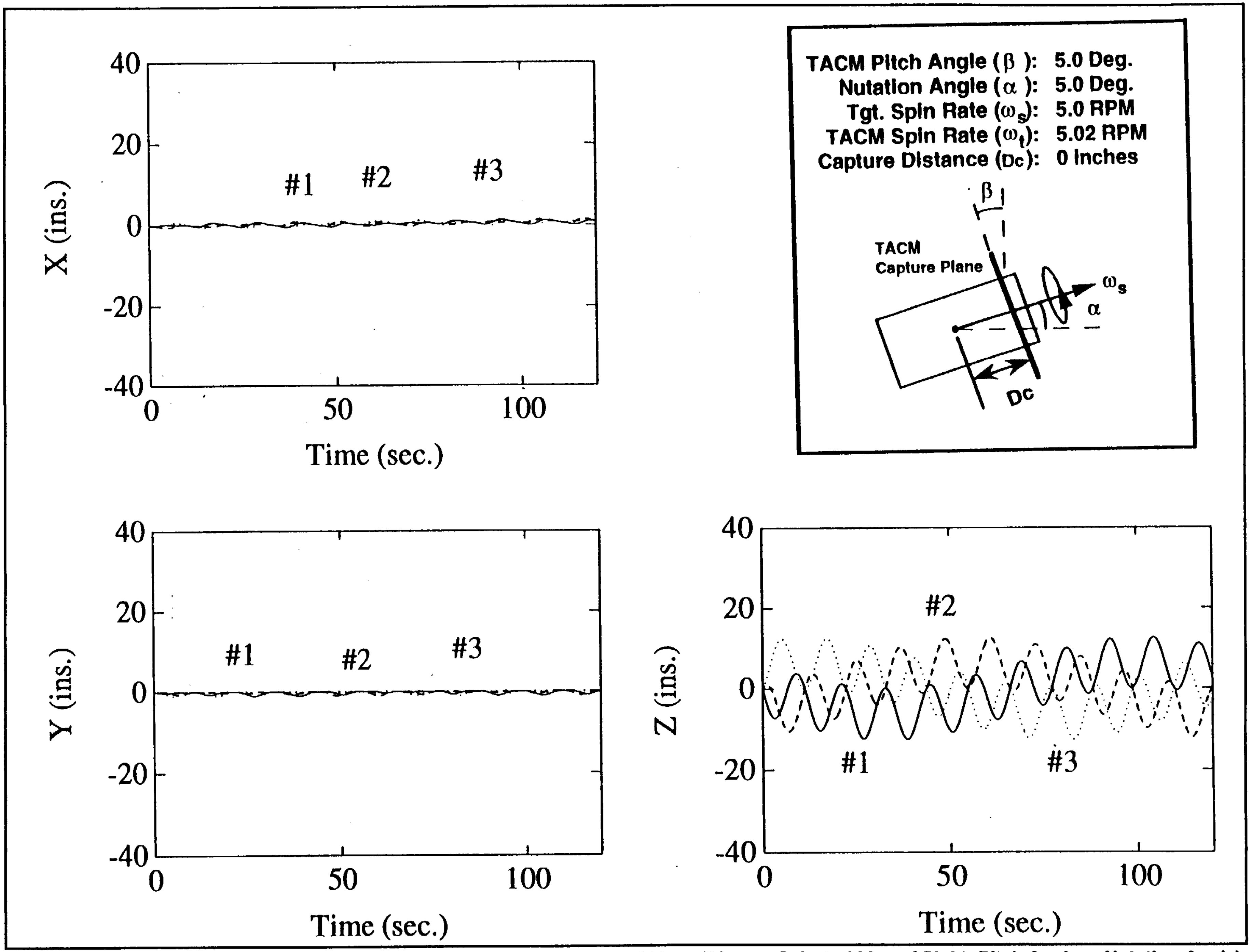


Fig. 3-15 Motion of a Point on a Precessing Satellite Through the Center of Mass (Along a Selected Line of Sight; Pitch Angle = Nutation Angle)

actuator at a rate that approximates the rate of travel of the satellite in that direction. For the case of an Intelsat 6, this would require a maximum rate movement of 0.5 inches per second. Postulating that we make contact with an Intelsat 6 class satellite that is rotating at a rate of 5 RPM with a nutation angle of 5 degrees, a momentum transfer of approximately 200 slugs-ft^2/sec is required to circularize the travel of the satellite. Once a pure spin condition is attained, slow spin table breaking can bring the satellite to rest at a rate consistent with the performance capability of the host ACS. Using the above capture methodology, a TACM capture mission is feasible. Additional analysis work is required to gain a more detail understanding of the contact dynamics of the problem.

3.2.5.2 The Need for an Integrated Control Scheme

Successful automated capture of a precessing satellite requires the coordinated movement of all three TACM arms, controlled rotation of its spin table, and host vehicle reaction jet supervision based on data derived from TACM image, distance and contact sensors.

An integrated TACM control system is required to command the host vehicle control system to provide reaction control jet firings and move the active TACM elements in support of the capture operation. The overall control system is made up of three parts, each possessing the capability of coordinated independent action, as required by the overall control logic.

Target Satellite Recognition System - This system is responsible for initial target recognition and determining the periodic motion state and relative location of the target satellite. The image recognition system provides inputs, based on desirable approach algorithms, so that the TACM can approach the target in the best orientation that enables capture along the vector in which contact forces are minimized. Based on developed rules of engagement contained in the TACM main computer processor, orbital maneuvering instructions are forwarded to the host vehicle to orient the capture device normal to the determined plane of capture. The vehicle then proceeds slowly in that direction, always updating and checking the updated feature information with its data base. Change/update commands are transmitted to the host vehicle. As the TACM kit approaches the target vehicle, the arm synchronization system is activated.

Arm Synchronization System - This system takes the input delivered by the image recognition system and implements spin table and arm motions to attain near motion matching conditions with the satellite. The mechanism arms will open to a diameter sufficient to reach beyond the maximum envelope of the target satellite, based on the input received from the image processing system. The depth of penetration of the TACM kit beyond the initial plane of the target vehicle is based on a predetermined capture plan (responding to reach capability, postulated target vehicle center of mass, and target vehicle geometry). Once the plane of penetration is reached, beyond the initial intersection plane, the arms will slowly close to just beyond the maximum amplitude motion of the path of the adjacent satellite surface.

Pad Contact System - The final stage involves a coordinated action to close on the target vehicle using the capture arm pads. Each pad system has a fast, fine-increment actuator system with about 20 inches of travel. The purpose of this system is to initially track any eccentricity during the final stages of capture, thus minimizing the requirements of moving the major arm systems and thereby causing additional host vehicle stabilization requirements. The motion of each pad is coordinated to slowly provide simultaneous contact. Once contact is made (with minimum force applied), the pad actuator movements deliver the desired controlled force application to the satellite which prevents undesired levels of reaction forces and slowly brings the captured satellite under control. Pad force sensor information supports the onboard capture control logic. Further application of restraint forces are then imposed to facilitate despin and controlled rigidization.

4 Support Data

4.1 Envelope configuration

The three-arm capture mechanism, as shown on Fig. 4-1, is capable of capturing an object that has a maximum diameter of 160 inches, assuming the TACM can approach the object normal to its principle axis. For an assumed nutation angle of 5 degrees, the maximum capture diameter will decrease to approximately 150 inches. These capture envelope estimates do not consider required space requirements for sensor depth sensitivity nor mass momentum effects. The TACM configuration allows capture of these larger object only at their outer most extremities (see Fig. 4-1).

The smallest size object that the TACM could capture, based on geometrical considerations, would have a diameter of 14 inches. The limiting condition is the concurrent touching condition of the three pads.

Each arm is approximately 72 inches in length and is composed of a two link mechanism, each controlled by a linear actuator. The tip section has an additional actuator that can move 15 inches radial to the mechanism major axis.

The basis for mechanism sizing was an Intelsat 6 class satellite that is 143 inches in diameter and 172 inches long. The mechanism can grasp this object at a depth of 65 inches assuming a pure spin initial condition. Assuming this object may be precessing, the mechanism can deal with a nutation angle up to 12 degrees on a geometrical basis; mass moment dynamics interactions would have to be analyzed to provide limiting operational capture conditions.

Assuming a totally cooperative target satellite, its mass effects on the capture operation would be of secondary order if we place no time constraints on the capture mission. Realistically there will be limiting mass that the TACM

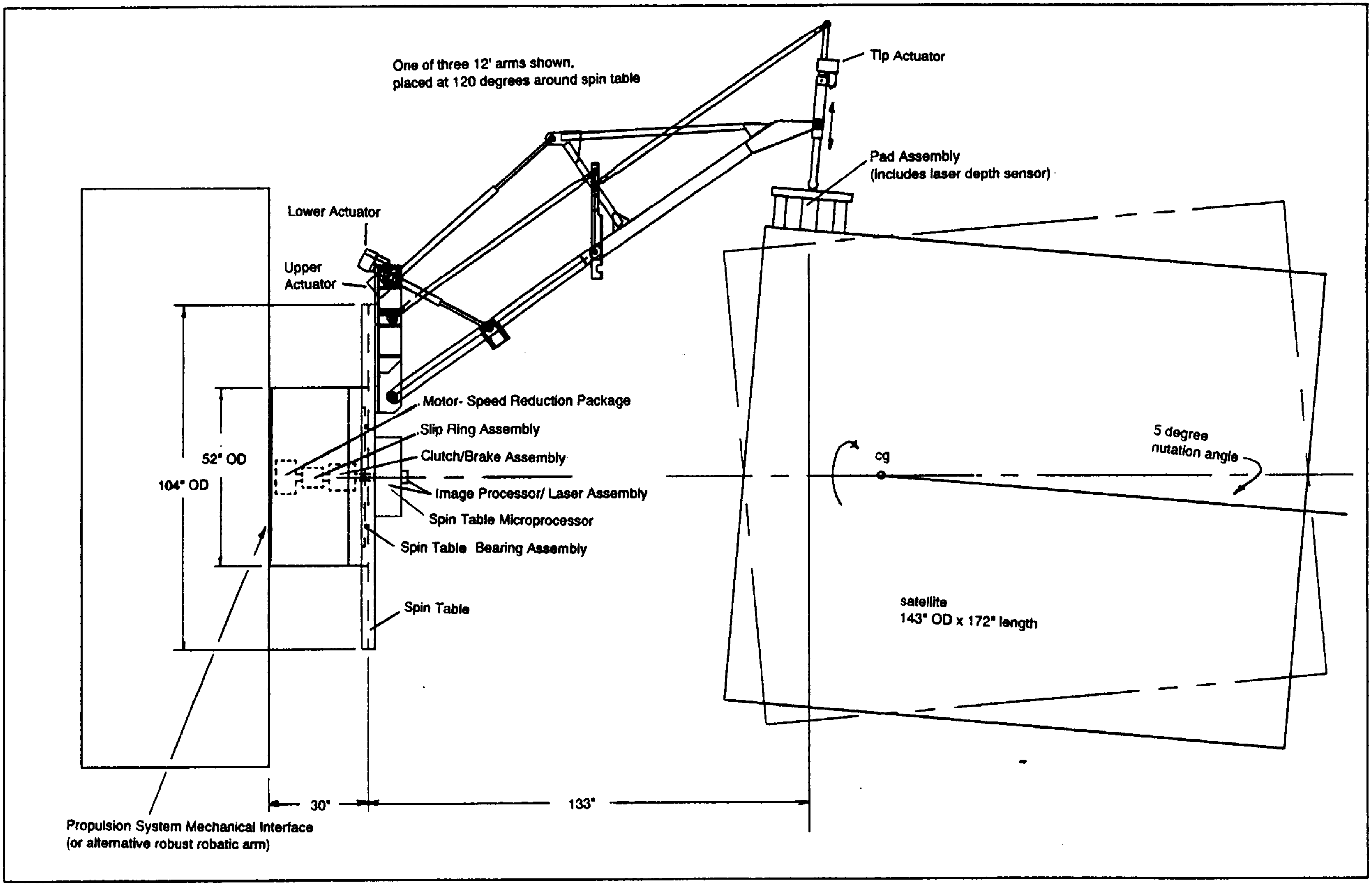


Fig. 4-1 TACM Concept

should be designed to capture; this will have to be determined based on analyses of structural and probable impact dynamics considerations and the capabilities of the host vehicle which is to provide a stable platform.

4.2 Weight

The weight estimates are based on the existing ground demonstrator test article configuration, revised for projected flight size requirements. A computer code was used to provide data on structural loads to ensure that the configuration was within allowable values during spin up. A limiting case of 10 RPM was used to evaluate the link structure. More determinate load and strength analysis is required for the arms under contact dynamics conditions to generate better weight information. The former requires more extensive analysis beyond the scope of this study.

Spin table structure weights are representative based on cantilever load considerations and space needed to locate equipment. The weight of components are based on available commercial data since applicable flight weight components do not exist.

Table 4-2 presents a summary of the major elements of weight of the mechanism together with the parameters used for developing the weight estimates.

4.3 Power

Fig. 4-3 provides estimated maximum power consumption for each major component using an assumed basis of a 28 Volt regulated power supply. The estimates are to be considered order of magnitude since they are developed from available commercial equipment. It appears that significant power draw requirements are needed for the major actuators;this requirement is not prolonged and is only perhaps needed during rigidization. Work-around to

TACM Element	Subelement	Component	Weight	Basis Used for Estimated Weight
Spin Table Assembly	Spin Table	Structure	250	Estimate
	Motor drive assembly	Motor& speed red.	15	based on HP requirement
		Clutch/brake ass.	10	Estimate
		Shaft	10	Estimate
		Slip ring assembly	5	Vendor input
	Arm #1	actuator (lower)	19	Ground demo hdwe scaled to size
		actuator (upper)	21	Ground demo hdwe scaled to size
		structure (lower)	25	Ground demo hdwe scaled to size
		structure (upper)	27	Ground demo hdwe scaled to size
		pad (actuator)	6	Vendor info based on requirement
		pad structure	26	Estimate
		pad laser	5	Vendor information
	Arm #2	actuator (lower)	19	Ground demo hdwe scaled to size
		actuator (upper)	21	Ground demo hdwe scaled to size
		structure (lower)	25	Ground demo hdwe scaled to size
		structure (upper)	27	Ground demo hdwe scaled to size
		pad (actuator)	6	Vendor info based on requirement
		pad structure	26	Estimate
		pad laser	5	Vendor information
	Arm #3	actuator (lower)	19	Ground demo hdwe scaled to size
		actuator (upper)	21	Ground demo hdwe scaled to size
		structure (lower)	25	Ground demo hdwe scaled to size
		structure (upper)	27	Ground demo hdwe scaled to size
		pad (actuator)	6	Vendor info based on requirement
		pad structure	26	Estimate
		pad laser	5	Vendor information
Spin table proc.			15	Estimate
Structure	Structure		150	Estimate
	Bearing		100	Estimate based on ground hdwe
Image processor	Processor& volt. reg		18	Estimate -ground application
	Camera		5	Estimate
Base laser			5	Vendor information
TACM Main Processor			15	Estimate -ground application
Subtotal			987	
Contingency (20%)			197	
Total			1184	

Fig. 4-2 Capture Kit Weight Summary

TACM Element	Subelement	Component	Peak Amps at 28V
Spin Table Assembly	Motor drive	Motor	5
	Arm #1,2,3	actuator (lower)	18*
	Arm #1,2,3	actuator (upper)	33*
	Arm #1,2,3	pad (actuator)	5
	Arm #1,2,3	pad laser	0.5
	Spin table proc.		2
Image processor	Bus Chassis and cards		5
	Camera		1
	Lighting		3
Base laser			0.5
TACM Main Processor	Bus Chassis and cards		5
notes * only used possibly for rigidization			

Fig. 4-3 Capture Kit Power Consumption Summary

minimize the current draw requirements across the slip rings include possible location of a battery on the spin table side with a trickle charge. Since we are not under a strict time requirement to complete the mission such alternatives could be considered.

4.4 Data and Power Processing Requirements

The data processing requirements for a mission that is performed under supervised autonomy is considerably larger than one under teleoperation. The input and command logic normally exercised by the operator must be included within the flight segment contained computer memory. This is in addition to the control logic that is present for flight vehicles under administrative pilot control. This section attempts to provide a first order estimate of the processing power and data flow requirements to perform such a mission.

The TACM electronics package consists of a main processor on the host vehicle connected via slip rings to the spin table and image processors on the spin table (Fig. 4-4). Two VME busses house the processors, one on each side of the slip rings, providing power and communications between the processors and the various I/O and sensor cards. The processors are 32 bit low power CMOS devices with sufficient speed and memory to handle the anticipated processing loads. A real time operating system (RTOS) kernel ensures the timely operation of individual processes within each processor. The modular nature of the VME bus RTOS architecture simplifies the addition of additional memory and/or processing power, should the need arise.

The main processor drives the spin table motor and brake, and reads the spin table encoder via a VME I/O card, simplifying upgrades for changing mission requirements. Host vehicle and slip ring communication is handled by the processor directly.

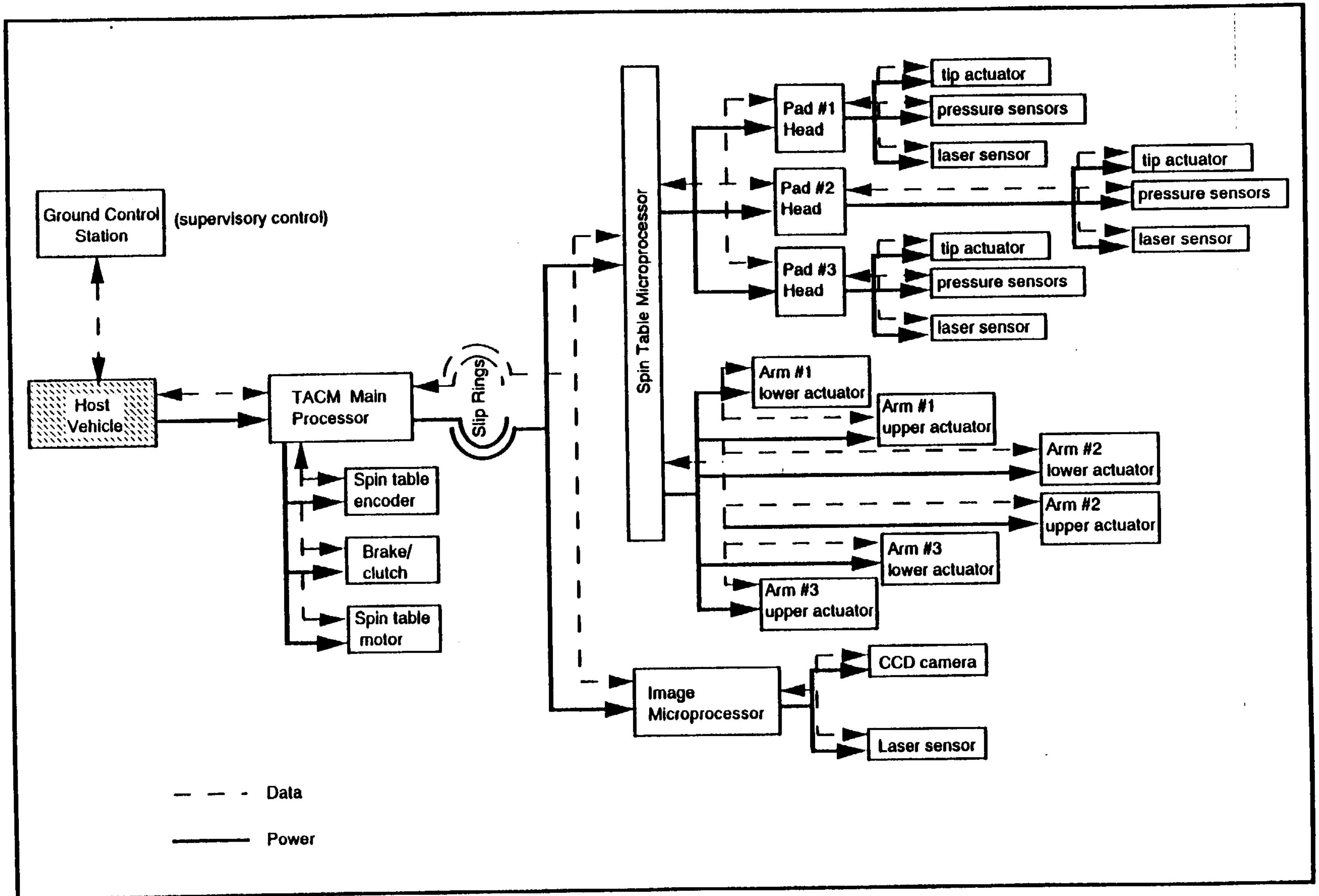


Fig. 4-4 TACM Control and Power Distribution Scheme

The Spin Table processor controls the arm actuators through a VME I/O card, while interfacing to the pads through pad head electronics mounted remotely near each pad. The pad head electronics perform low level sensing and control, off loading these functions from the spin table processor and reducing the need for substantial sensor and actuator arm wiring. Sensor noise is reduced by eliminating these lengths of wire and keeping the analog sensing electronics away from the processor.

The image processing system runs onboard a dedicated processor card on the VME bus, as the functions it must perform are both computationally and data intense. It receives data from the CCD camera and laser sensor interfaces, and communicates with the spin table processor through the VME bus and the TACM processor via the slip rings.

Figure 4-4 presents a concept schematic for the control and power distribution for the TACM. In general, as much as possible of the control logic should be retained on the host vehicle side of the spin table slip rings. In like manner, where there is a high processing load as in the image processor, only necessary information should transmitted across the slip rings; the bulk of the processing should be performed on the side where the sensors are located.

Figure 4-5 presents the estimated distributed processor sizing for the TACM concept. Identification of sensory items and functional processor operations are provided as a basis for sizing. A distributed processor architecture is envisioned to increase response sensitivity of pad force reaction capability.

4.5 Host Vehicle Support Services

The mechanism is attached to a host vehicle. It is assumed that the host vehicle will provide all reactive load compensation to maintain a stable work platform for the three-arm capture mechanism. It will be responsible for maintaining a power source for the mechanism. Communication with the

Item	Number Required	Estimated Size	Sensory Items	Functions
Pad head cards	3	na	pressure sensors actuator speed actuator position laser inputs	**internal processing** '- average pressure data '- actuator speed control '- actuator position control '- distance calculation '- laser control '- side load calculation **communications** '- applied pressure '- distance to object '- side loads '- receive actuator control commands
Image Processing Microprocessor	1	32 bit	camera ranger image digitizing input	**internal processing** '- image pixel processing '- CAD data base matching '- (laser) distance calculations '- motion predictions '- inertal position mapping '- local area feature mapping '- spin table control requirements **communication** '- interface with vehicle control '- image classification results '- image map '- opertional commands
Spin Table Microprocessor	1	32 bit	actuator position inputs actuator speed inputs strain gages	**internal processing** '- main actuator speed control '- main actuator link control '- main actuator position '- actuator loads **communication** '- provide status data '- accept actuator operations commands
TACM Main Processor	1	32 bit	motor control inputs motor encoder inputs brake inputs applied load inputs host vecicle status ground commands	**internal processing** '- store overall capture logic '- interface with all other processors '- formulate operations instructions '- assess and issue safety commands **communications** '- host vehicle interface and commands '- other TACM microprocessor interfaces '- provide mission commands '- receive actuator control commands '- status conditions

Fig. 4-5 Estimated TACM Processor Sizing Basis

ground station for operator supervisory commands and downloading of mission data is assumed to be performed through this interface. All necessary data compression to improve transmission to the ground is assumed to be performed on host vehicle systems

5 Development Work

5.1 Programmatics

Significant progress has been made on the satellite capture issue using ground simulations. Teleoperated capture scenarios of stationary, spinning, and precessing (off-axis spin) satellites have been performed in the laboratory.[7,8] To take this effort to the next level of maturity towards autonomous operation, engineering and laboratory work must be directed towards the sensory area and the problems of target satellite recognition, controlled approach and dynamic capture.

Based on the results of this effort we contend that the existing demonstration hardware delivered by Grumman to NASA/MSFC is suitable for one-half scale ground simulation work, considering the size of existing communications class satellites as capture targets. The efforts needed to augment the existing hardware for automated capture missions, albeit with remote operator supervision, consists of the following:

1. Initiate work to develop an image recognition system that would identify the shape of a target and characterize its movement based on comparison with data base information. This system may also be called upon to provide information on distance of the target from the vehicle. The candidate equipment needed for this task is presently envisioned to include two parallel sensor systems: a 2-D CCD camera system and a laser mapping system. Simulation and laboratory work is required to demonstrate the functionality of system elements, confirm that functional requirement allocation is correct, and establish the desired interfaces between these two sensory elements. Both system elements must work within an overall control philosophy that directs the vehicle to orient itself along the desired capture path vector. This process would involve investigating existing candidate systems that apply and formulating a

detailed plan for integration of their output data, developing a logic for the overall vision recognition task and ensuring that the system elements complement the selected capture control approach. Ultimately one system element could be chosen over the other, or one of them could become a less sophisticated system - these decisions cannot be made at this point.

2. Initiate a detailed computer modeling activity to characterize the momentum transfer dynamics of two bodies, the concept three-arm capture mechanism and the target satellite being captured.

3. Institute laboratory work to select/develop a ranging system for the arm tip assembly.

4. Upgrade the existing test article according to the results obtained from the sensor work above and additional support hardware, such as the arm tip pad actuators.

The order of presentation above, with items 1 and 2 taken together, indicate the suggested sequence of activities that need to be performed.

The vision processing system is furthest from a mature element for our application and is very important to the success of supervised autonomous capture. Work being performed in developing generic vision systems that perform feature recognition is starting to show progress; these efforts must be focused on our application. Decisions then can be made on their direct applicability and required modifications to facilitate the successful completion of satellite capture.

The control approach philosophy must be derived from analysis of the specific two-body dynamics application. The momentum transfer rates when the target satellite first contacts the mechanism arm pads must be analyzed to generate operational control logic to provide counter forces through the mechanism interfaces that tend to null out the precession of the satellite. These analysis results must be investigated towards developing a control logic that does not result in off-nominal forces for the mechanism or satellite structure.

A ranging system for each arm tip, while not directly available for flight use, appears to be further along technology development. There already exists similar hardware, albeit used in earth applications; it has to be reoriented to our requirements.

Figure 5-1 presents a plan for development of the first two elements. Analysis of the major areas (image recognition and control dynamics) must first be performed. Once completed, it is proposed that computer graphical representation of the analysis results be used as the vehicle to analyze how the vehicle control logic should be implemented to perform capture while maintaining a stable mechanism platform. The computer simulation provides an opportunity to verify postulated sensor data stream rates and image pixel thresholds for performing efficient target characterization. Further commitments on laboratory hardware can proceed with less risk. A complete hardware simulation series can then be performed, more from a verification point of view than an initial investigatory sense. Once these first two elements have been developed as ground demonstration applications using the existing test hardware, we will have progressed to proceeding with a ground test demonstration. The facilities at MSFC can readily accommodate all requirements for the complete simulation scenario. Upon conclusion of the ground test program, sufficient engineering data will have been compiled to enable proceeding with a flight demonstration effort.

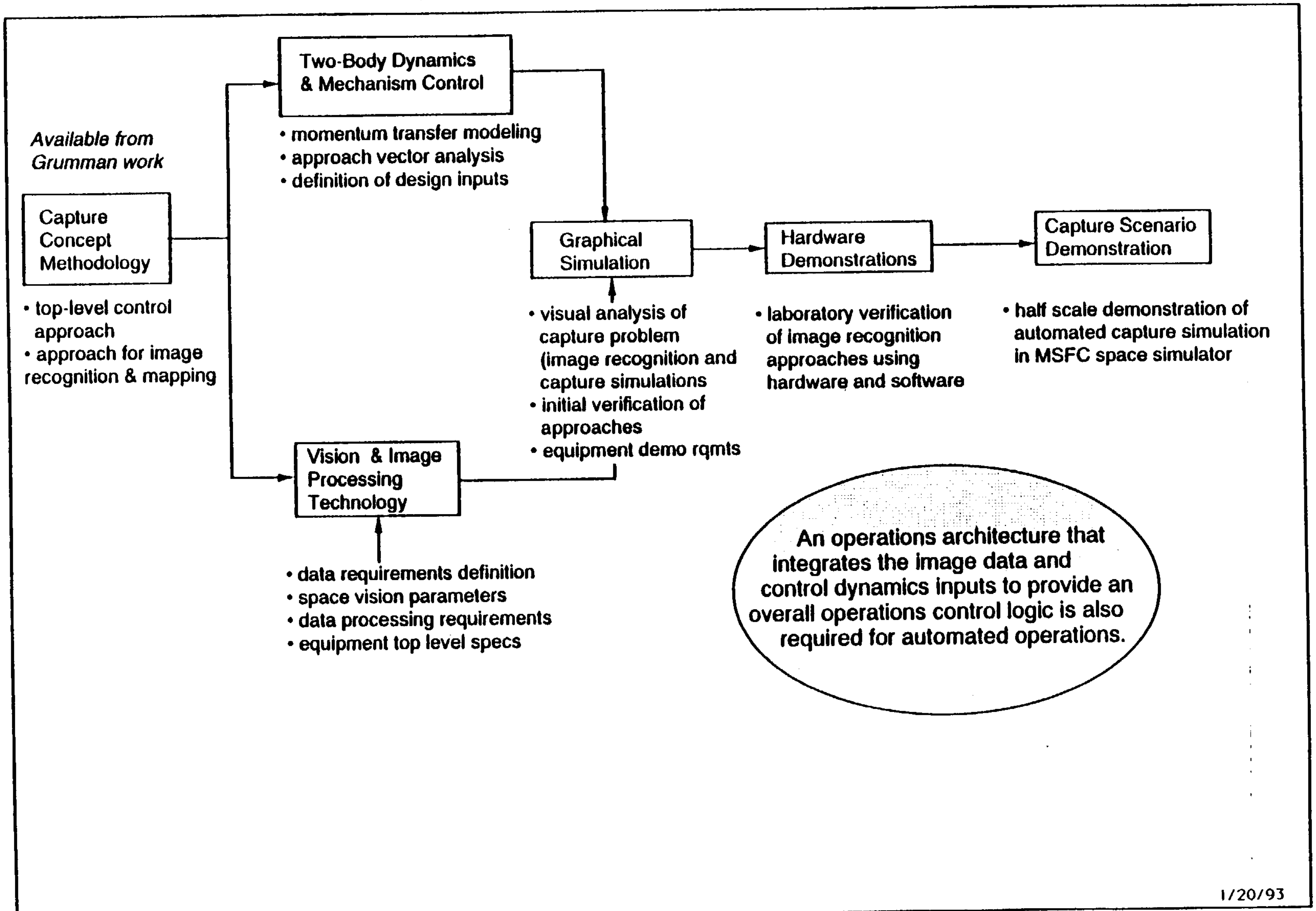


Figure 5-1 Development Plan for Automated Capture and Target Satellite Recognition Technology

Appendix

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10. Laser Atlanta, Norcross , GA

11. Multiple-Plane Range Acquisition Sensor (MPRAS) System by Intelligent Automation Systems, Inc., Cambridge, MA

12. *Space Shuttle System Payload Accommodations, NSTS 07700 Volume XIV, Appendix 8, System Description and Design Data - Payload Deployment and Retrieval System, Rev. J, 5/2/88*