ADVANCED ROBOTICS FOR IN-SPACE VEHICLE PROCESSING

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ABSTRACT

An analysis of spaceborne vehicle processing is described. Generic crew-EVA tasks are presented for a specific vehicle, the orbital maneuvering vehicle (OMV), with general implications to other on-orbit vehicles. The OMV is examined with respect to both servicing and maintenance. Crew-EVA activities are presented by task and mapped to a common set of generic crew-EVA primitives to identify high-demand areas for telerobot services. Similarly, a set of telerobot primitives is presented that can be used to model telerobot actions for alternative telerobot reference configurations. The telerobot primitives are tied to technologies and used for composing telerobot operations for an automated refueling scenario. Telerobotics technology issues and design accommodation guidelines (hooks and scars) for the Space Station *Freedom* are described.

Title

INTRODUCTION

The development of Space Station *Freedom* involves a multiplicity of large-scale space systems and a number of space vehicles are required to support a broad variety of station operations. Most prominent are the Orbital Maneuvering Vehicle (OMV) for near-Earth operations and the Space Transfer Vehicle (STV) for near-Earth and Earth-Lunar operations. Because the station and these vehicles are at various stages of development, there is a twofold interest in examining the potential for applications of robotics technology to vehicle processing. The first interest is in understanding the functional operations to be performed in the future station environment. The second interest is in understanding the potential design accommodations that robotics might require of the station--the so-called hooks (software accommodations) and scars (hardware accommodations) needed to ensure that future technology developments can be accommodated by Space Station *Freedom*.

ANALYSIS OF VEHICLE PROCESSING OPERATIONS

Space operations will involve large quantities of crew-EVA to perform a variety of tasks such as assembly, servicing, maintenance, and inspection. The requirements for housekeeping and servicing are typically stated in terms of budgeted crew-EVA hours for the tasks involved. Simply stated, EVA requirements are the "work" that needs to be performed to keep the spacecraft system in operational order and perform its mission(s). The task analysis seeks to optimize available EVA excursion time by planning in detail, the primitive subtasks to be performed. The term used for these human-performed primitive subtasks is "crew-EVA primitives." In a similar fashion, a set of "telerobot" primitives is defined for machine performance of tasks. The telerobot primitives are linked to technologies and assembled into procedures for performance of telerobot operations. The study establishes a common language to better understand the relationship between generic crew-EVA tasks and potential telerobot performance of such activities.

Figure 1

EVOLUTION PLANNING FOR ADVANCED DEVELOPMENT

OBJECTIVE

DEVELOP AN EVOLUTION PLANNING METHODOLOGY THAT MAPS EVA REQUIREMENTS INTO AN A&R TECHNOLOGY DEVELOPMENT PLAN

SELECT REFERENCE MISSIONS (On-Orbit Vehicle Proc.)
- OMV Servicing (incl. refueling & Inspection)
- OMV Maintenance (ORU Changeout)

DEFINE & SCRIPT REFERENCE SCENARIOS & DEVELOP MISSION TIMELINES

Develop EVA Primitives

TRANSLATE ACTIVITIES INTO EVA PRIMITIVES & IDENTIFY CANDIDATE ACTIVITIES FOR EVA DISPLACEMENT

Develop Tele-Robot Primitives

TRANSLATE EVA PRIMITIVES INTO TELE-ROBOTIC PRIMITIVES

DETERMINE A&R TECHNOLOGY DEVELOPMENT REQUIREMENTS

DEFINE STATION HOOKS & SCARS TO FACILITATE A&R IMPLEMENTATION

INTEGRATE RESULTS INTO A PLAN FOR A&R TECHNOLOGY DEVELOPMENT

METHODOLOGY

The starting point for development of the study methodology was to collect empirical descriptions of the performance of a number of crew-EVA tasks, including "timeline data" that records the duration of successive segments of each task from Space Shuttle-based EVAs. The analysis proceeds hierarchically from projected task demands for user payloads and station and vehicle servicing and maintenance to the definition of generic crew-EVA tasks, activities, and primitives. A set of crew-EVA primitives are defined and each EVA task is segmented into a setup, kernel, and closeout activities. The crew-EVA primitive set is used to calibrate a generic model for estimating the EVA impacts of the given task. This study developed the following generic crew-EVA tasks at the task, activity, and primitive levels:

SSF Housekeeping

- Truss Assembly (SSF)
- ORU Changeout (SSF)
- Payload Changeout
- Servicing/Repair

Vehicle Processing (OMV)

- Truss Assembly (Planetary Vehicle)
- ORU Changeout (on OMV)
- Servicing (OMV refueling)
- Payload Integration

Figure 2

STATION-BASED OMV SERVICING TIMELINE

TIME (MIN)	IVA	EVA-1	EVA-2
0		Egress Airlock	Egress Airlock
0–5		Translate to tool locker	Translate to tool locker
5–10		Retrieve servicing tools, foot restraints & sensors	Retrieve servicing tools, foot restraints & sensors
15	Grapple MFR with RMS (EV1 assist)	Grapple MFR with RMS (EV1 assist)	Translate to OMV processing area
20	Standby	Configure MFR on RMS	Configure peripherals
25	Position MFR	Ingress MFR & translate to OMV	
30		Remove covering from umbilical port	Remove covering from refueling port
35–40	Verify I/F	Connect the OMV power & signal umbilical / verify interface	Connect the OMV power & signal umbilical / verify interface
40–45	Command OMV to station mode		
45–55	Load & run self-test program for propulsion system	Unstow & install OSCRS refueling hoses & leak detection sensors / checkout	Unstow & install OSCRS refueling hoses & leak detection sensors / checkout
55–60		Purge line with GN2 & inspect for leaks	Purge line with GN2 & inspect for leaks
60–70		Configure valves for hydrazine transfer	Configure valves for hydrazine transfer
70–115	Operate the APM/RMS	Conduct visual inspection of OMV	Monitor hydrazine fuel transfer
95–120			Monitor hydrazine fuel transfer
115–120	Operate the APM/RMS	Remove meteor/thermal covering from four GN2 refueling ports	

METHODOLOGY AND RESULTS

This figure illustrates the analysis process for a portion of the OMV servicing timeline by aligning the crew-EVA and equivalent telerobot-EVA primitives on the same timescale. Because of limitations inherent to the machine-performed task, the quantity of assumptions, descriptions, and definitions is inherently larger. The objective of this process is to explicitly map the telerobot operational timeline in order to surface technology and operational limits. The model used to estimate the generic crew-EVA times for each task, activity, and primitive is:

$$X^t_{S_j} + \sum_{i=1}^{4} X^t_{K_{ij}} + X^t_{T_j} = Y^t_j \quad (j = 1, \ldots N)$$

where:

$X^t_{S_j}$ $\equiv$ Setup time (hours) for activity j within time period t.

$X^t_{K_{ij}}$ $\equiv$ Task kernel time (hours) for activity j, category i, and time interval t.

$X^t_{T_j}$ $\equiv$ Teardown time (hours) for activity j within time period t.

Y^t_j $\equiv$ Total time for crew-EVA excursion number j within time interval t.

Note that the actual times, $X^t_{(*)}$, are sums of the product of task primitive standard times and frequency of occurrence:

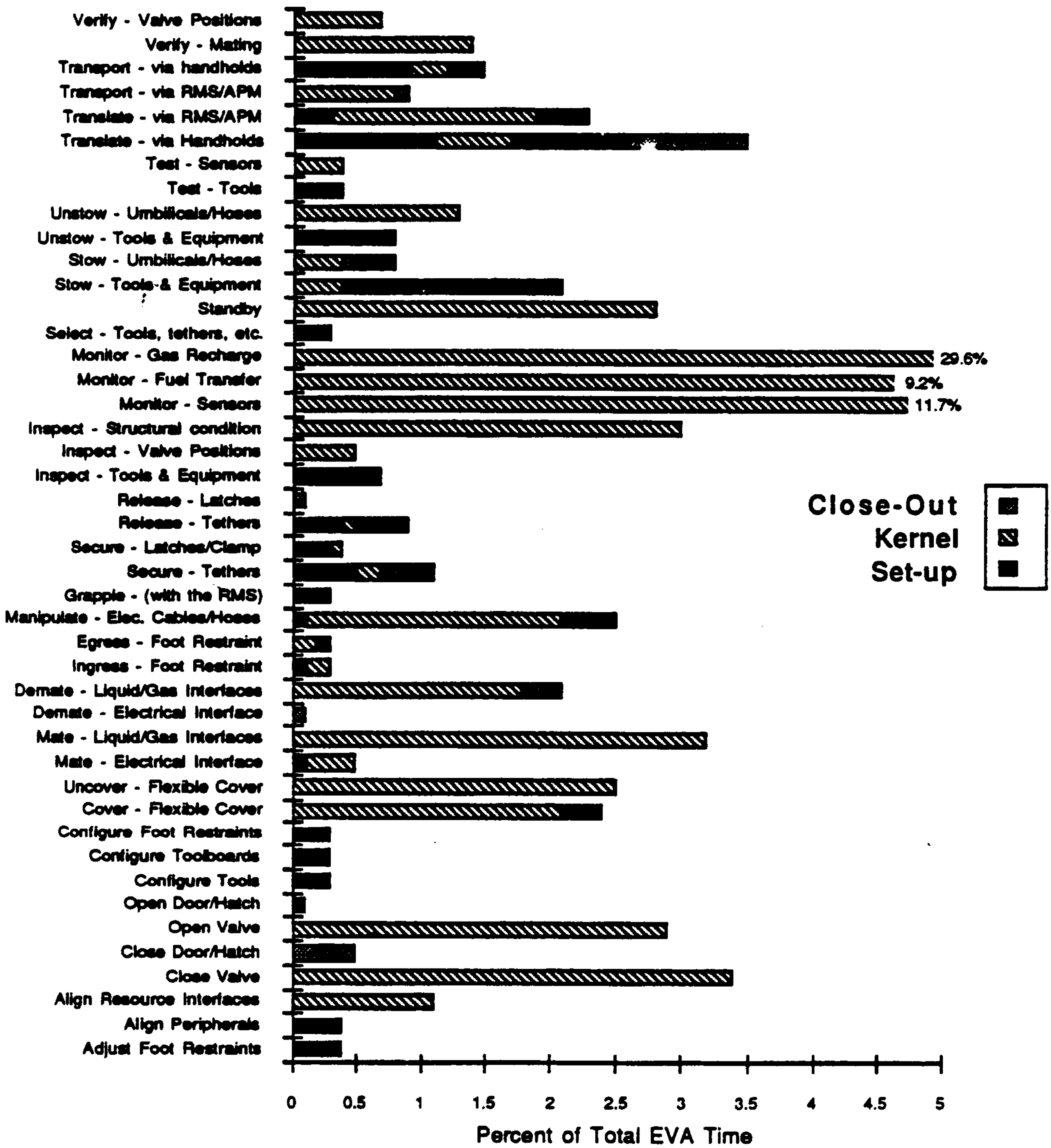
$$X^t_{S_j} = \sum_{m=1}^{n} \pi_m \cdot f_{S_m} \qquad X^t_{K_j} = \sum_{m=1}^{n} \pi_m \cdot f_{K_m} \qquad X^t_{T_j} = \sum_{m=1}^{n} \pi_m \cdot f_{T_m}$$

where, n = the total number of task primitives
π_m = standard time to perform task primitive m (minutes).
$f_{(*)m}$ = frequency of task primitive m for $* =$ S, K, or T.

By dividing generic task times into standardized times multiplied by frequency, a *standardized* timeline is obtained for each of the generic crew-EVA tasks. The standardized times are a powerful result that can be extended to other tasks. The problem of calculating task times is thus transformed from estimating highly variable task-specific times to one of estimating the number of times each generic task is to be performed.

Figure 3

OMV SERVICING EVA PRIMITIVE SUMMARY



RESULTS (CONTINUED)

Because there are empirical data on which to standardize the generic crew-EVA activities and primitives, time estimates for each of the generic tasks is estimated probabilistically using the above model. This figure illustrates the proportion of time spent performing each crew-EVA primitive as a fraction of the total EVA excursion time. Such analyses focus attention on promising areas for telerobot operations such as translation, monitoring (inspection), and selected opening and closing manipulations.

Figure 4

SET-UP OMV SERVICING ACTIVITIES

1. Translate to Tool Locker

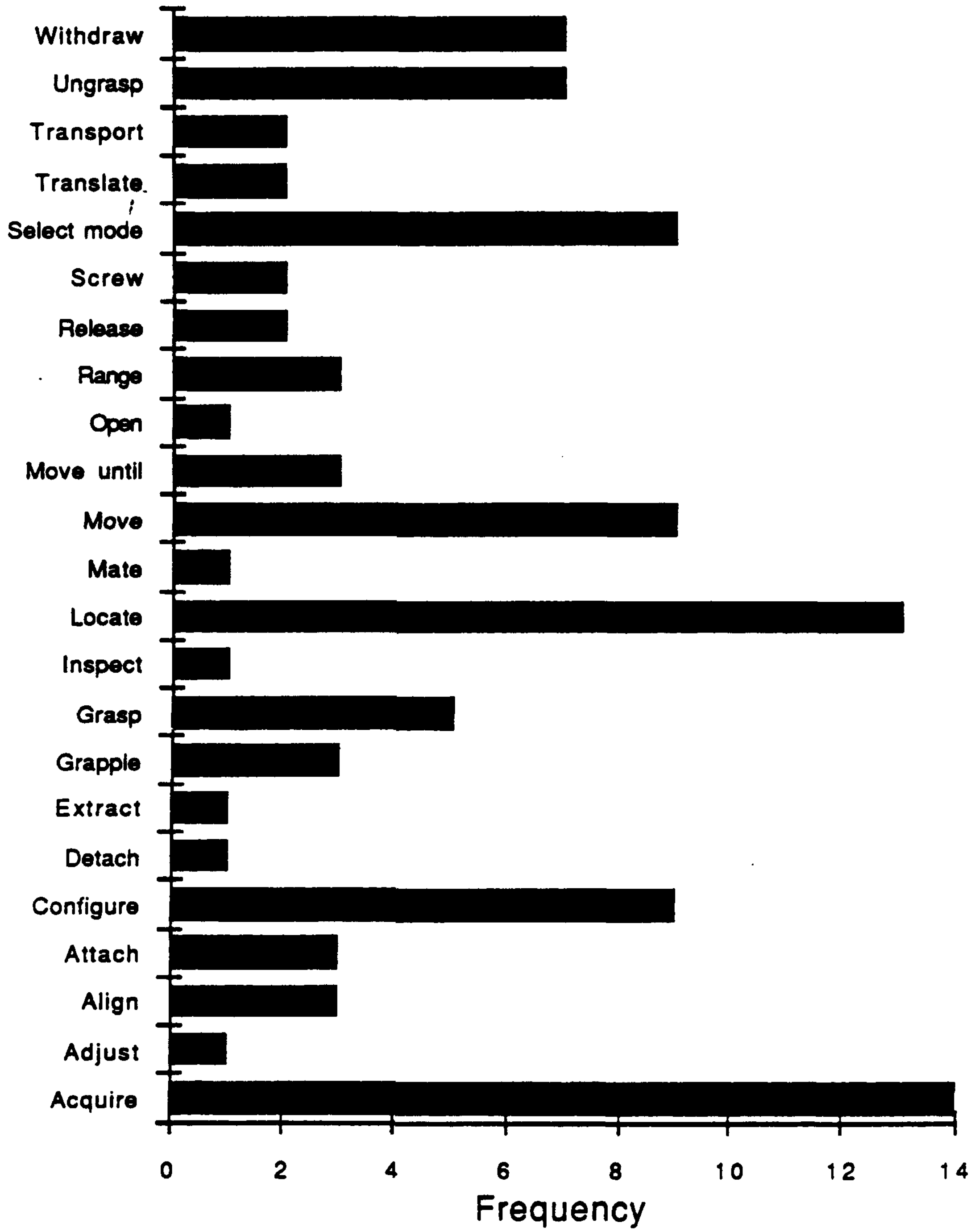
EVA Primitive	Equivalent Telerobot Primitive(s)
Translate (via Handholds)	Select mode, Configure, Acquire, Range, Translate

2. Retrieve Servicing Tools, Foot Restraints, & Peripherals

EVA Primitive	Equivalent Telerobot Primitive(s)
Secure (tethers)	Select Mode, Configure, Acquire (grapple fixture), Locate, Move, Grapple It is assumed that grapple fixtures will be required at the tool site to stabilize the robot during tool selection. This is equivalent to tethering, used by EVA crewmembers to stabilize themselves.
Open (door)	Acquire(door handle), Locate, Move, Grasp, Open, Ungrasp It is assumed that tools will be stored inside a tool cabinet which is accessed by means of a hinged door.
Select (tools, periph.)	Acquire (tools, periph.), Locate, This activity occurs in conjunction with unstowing. It addresses the time element involved in recognizing the tool(s) being searched for. The robot will recognize the tool by means of matching the sensed image with an image in the robots tool library.
Unstow (tools, periph.)	Move, Grasp, Detach, Extract (from tool cabinet) Tools are assumed to be secured within the tool cabinet either by means of a snap in/out arrangement, or by means of a velcro interface.
Configure (toolboard)	Acquire (toolboard), Locate, Attach (tools to tool-board or EMU) This involves attaching tools & equipment to the EMU or toolboard by means of short tethers or velcro.
Inspect (periph.)	Inspect
Release (tether)	Release (grapple fixture), Withdraw EVA crewmembers will untether to free themselves from restraint. The robot will merely release the grapple fixture.

This figure illustrates the frequency of telerobot primitives for the set-up phase of the generic OMV servicing task. Because there is little, if any, analogous timeline data for telerobot operations, the frequency of primitive occurrence is used as a guidepost to promising telerobot primitives for advanced development. Telerobot primitives with high frequencies may be the initial candidates for autonomous operation, however, as specific time estimates for telerobot performance become available from laboratories and test flight measurements, improved projections of high-value functions for autonomous operations will be possible.

ROBOT PRIMITIVE SUMMARY
OMV SERVICING SET-UP PHASE



CONCLUSIONS: RECOMMENDED ROBOT DESIGN FEATURES

There are a number of design features that, if incorporated into the station design, will enhance considerably, the ability of the station to accommodate new robotic technologies in the future. These conclusions are an attempt to characterize the major impact areas for robot hooks and scars.

Figure 6

RECOMMENDED ROBOTIC DESIGN FEATURES FOR SPACE STATION FREEDOM TO SUPPORT A&R

- Autonomous translation of mobile robotic devices and supporting structures (e.g., MSC, MRMS) may require position location sensors embedded in truss members, laser ranging devices on the vehicle and at locations on the station, or other built-in aids to tracking precise location over time.

- Payload retention interfaces used on STS, SIA, OMV, servicing facility, etc, should be standardized to minimize on-orbit reconfiguration req'ts.

- Remotely operated latches with manual over-ride should be used for payload retention to facilitate robotics. Manual overrides should be robot operable.

- Where built-in automatic umbilical mating/demating devices are not employed, umbilicals should be robot compatible and located where adequate space is available for access and manipulation, and robot retention fixtures should be availible for anchoring the robot.

- Peripherals (lights, cameras) and foot restraints should be compatible for robot manipulation and installation as a PMC Phase I capability.

- Power/data umbilical mating between the SSF OMV berthing facility and the OMV should be enabled to be performed remotely to reduce EVA.

- Data storage & processing requirements increase significantly with A&R evolution (i.e., worksite modeling, planning systems, system test/monitoring/fault diagnosis, etc). Hardware & software should be expandable, modifiable (flexible).

- Since flexible covers & tape are difficult for robots to handle, making thermal covers an integral ORU component or designing the cover for easy removal & installation will facilitate robotic efficiency.

- Design robot compatibility into ORU & tool storage
  - Easy access by RMS & robot
  - Docking points for robot stabilization
  - Visual alignment guides on ORUs, tools, & storage facilities to reduce precision requirements & force sensing complexity
  - Record of removal and replacement (inventory control)

- EVA hand & power tools should be robot compatibile, at least to the level of enabling human or robotic stowing or retrieval (robots may work more effectively with their own tools).

CONCLUSIONS: RECOMMENDED OMV DESIGN FEATURES FOR ROBOTICS

There are also a number of design features that would enhance the functionality of performing vehicle servicing robotically. This figure summarizes such features.

Figure 7

RECOMMENDED ROBOTIC DESIGN FEATURES FOR SPACE STATION FREEDOM TO SUPPORT A&R

ON-ORBIT OMV REFUELING

On-orbit transfer of hazardous fluids from one tank to another must be accomplished using remotely operated equipment with manual over-rides.

- Scar the OMV to facilitate remote/robotic refueling:
  - Manifold the cold gas system to provide single point recharge capability
  - Co-locate hydrazine, cold gas, & electrical connectors (accessible by an automatic coupling device)
  - Use standard interfaces for fluid connectors, plugs, etc.
  - Design protective/thermal covers on OMV refueling & electrical ports to be retracted automatically by the umbilical coupling device
  - Scar the OMV propulsion module for automatic on-orbit refueling (i.e., colocated refueling ports designed for automatic umbilical mating)