A Task-Based Metric for Telerobotic Performance Assessment

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ABSTRACT

Many proposals have been forwarded for evaluation task sets that would be used in the ground and flight testing of the NASA Flight Telerobotic Servicer (FTS). Thus far, though, few of the proposals have been accompanied by so much as an estimate, let alone an evaluation of the complexities of the tasks. Task complexity is not always intuitively obvious, and a complexity metric would serve to (A) determine whether the proposed task set truly envelopes the control complexity levels that will be required of the FTS for known missions, (B) measure the complexities of future tasks that may be proposed for telerobotics, and (C) evaluate FTS performance gains from new designs and new technology incorporation.

This paper describes a methodology for developing a task complexity index based on combining the six basic motion primitives (three translation, three orientation) with force control and accuracy requirements. The result of this development is a set of complexity values that can be assigned to the high-level task primitives derived from a relatively shallow top-down mission analysis. These values are then averaged to arrive at total average mission complexities, such as for the mission of exchanging the Hubble Space Telescope (HST) battery modules.

Application of this metric to a candidate set of FTS evaluation tasks is discussed using the HST battery module mission for an in-depth example.

MOTIVATION FOR A ROBOTIC TASK METRIC

The primary thrust of the NASA space robotics effort is in the development of remotely - controlled systems which are highly flexible in terms of performance capabilities. The Flight Telerobotic Servicer, for example, must be capable of exchanging modules ranging in size from a few cubic inches to roughly phone booth dimensions, and must interface with and manipulate a large variety of fastener types, rigid geometric shapes, and even non-rigid materials.

The usefulness of these systems, and the confidence with which they can be applied will depend, in large part, on the ability to demonstrate satisfactory performance for the broadest possible envelope of task requirements during the development phase, and on the ability of mission planners to predict, with confidence, the system's performance for new task types, or variations of known ones.

To achieve this kind of assessment capability for the FTS development and operation, an approach must be derived to assign relative complexity (or performance difficulty) values to generic tasks. This complexity scale can then be used in a number of potential applications:

- As an aid in the selection of ground and flight test task panel operations to ensure the evaluation task set envelopes the range of difficulty of at least the known servicing tasks.

- As an evaluation metric in ground test-beds to assess the relative performance of candidate systems and subsystems, including human operators for teleoperation.
- As a mission planning tool to aid in the development of mission timelines and power consumption estimates.
- As a basis for determining which tasks should be performed by EVA astronauts versus robots.
- As an aid in determining the need for special tools and/or fixtures to perform particularly difficult operations.

PRELIMINARY COMPLEXITY SCALE DEVELOPMENT

To be useful as an evaluation tool for robotic system development, this metric must be task-based only, and independent of the mechanism performing the operation. Related studies (1,2,3) have generally considered some characteristic of the robotic mechanism in the analysis, usually for the purpose of determining optimal trajectories for the manipulator to perform the task.

Our initial work has focused on developing a metric using the six basic motion primitives - three translational and three rotational - in combination with the requirement for force control and high or low tracking, aligning, or orienting precision. These are the fundamental physical control elements with which most robotic tasks can be described.
A hierarchical description of task complexity was then derived, based upon the intuitive observation that the lowest level of complexity is a single motion primitive (MP), followed by sequential execution of MP's, followed by simultaneous execution of MP's. As a "first cut," it was assumed that the requirement for force control (FC) is less of a contributor to task complexity (or difficulty) than is the requirement for high precision tracking. Combining these task attributes into a complexity scale yielded the list shown in Table 1.

The complexity scale depicted in Table 1 arbitrarily terminates at the three sequential motion primitive level. Obviously the table could be carried out to the full six degree-of-freedom level, however it is difficult to envision, even in an unconstrained motion case, a task which requires more than three degrees-of-freedom of simultaneous motion.

A linear scale was used initially to assign values to the set, where the lowest complexity level is .06, and the highest level is one (1.0). The completed complexity scale with assigned values is shown in Table 2.

Using these complexity values, which are based on the very basic motion and control primitives, relative measures of complexity for generic task primitives, such as turning a crank, peg-in-the-hole, connect/disconnect, etc., can be assigned. Figure 1 shows examples of various representative robotic tasks and their corresponding complexities based on this preliminary methodology.

As can be seen, this approach accounts for the greater complexity (or difficulty) of installing a pin or bolt or connector versus removing them by specifying a high accuracy requirement for alignment, which corresponds to a higher complexity value. This is certainly realistic, since the motion constraints during removal eliminate the requirement for accurate positioning, making the task easier to perform.

To demonstrate the use of this metric in the evaluation of real satellite servicing tasks which may be candidates for ground and flight testbed task panels, the Hubble Space Telescope (HST) battery module exchange mission was analyzed.

COMPLEXITY LEVEL	DESCRIPTION
1	SINGLE mp, NO FORCE CONTROL (-FC), LOW ACCURACY (L)
2	SINGLE mp, FC, L
3	SINGLE mp, -FC, H
4	SINGLE mp, FC, H
5	SEQUENTIAL mps, -FC, L
6	SEQUENTIAL mps, FC, L
7	SEQUENTIAL mps, -FC, H
8	SEQUENTIAL mps, FC, H
9	SIMULTANEOUS 2 mps, -FC, L
10	SIMULTANEOUS 2 mps, FC, L
11	SIMULTANEOUS 2 mps, -FC, H
12	SIMULTANEOUS 2 mps, FC, H
13	SIMULTANEOUS 3 mps, -FC, L
14	SIMULTANEOUS 3 mps, FC, L
15	SIMULTANEOUS 3 mps, -FC, H
16	SIMULTANEOUS 3 mps, FC, H

Table 1. Complexity scale description

COMPLEXITY LEVEL	DESCRIPTION	VALUE
1	SINGLE mp, -FC, L	.06
2	SINGLE mp, FC, L	.13
3	SINGLE mp, -FC, H	.19
4	SINGLE mp, FC, H	.25
5	SEQUENTIAL mps, -FC, L	.31
6	SEQUENTIAL mps, FC, L	.38
7	SEQUENTIAL mps, -FC, H	.44
8	SEQUENTIAL mps, FC, H	.50
9	SIMULTANEOUS 2 mps, -FC, L	.56
10	SIMULTANEOUS 2 mps, FC, L	.63
11	SIMULTANEOUS 2 mps, -FC, H	.69
12	SIMULTANEOUS 2 mps, FC, H	.75
13	SIMULTANEOUS 3 mps, -FC, L	.81
14	SIMULTANEOUS 3 mps, FC, L	.88
15	SIMULTANEOUS 3 mps, -FC, H	.94
16	SIMULTANEOUS 3 mps, FC, H	1.0

Table 2. Complexity scale with linear value set

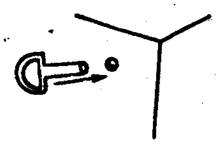
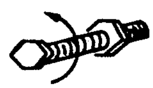
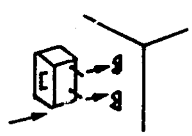
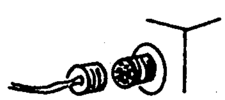
Task Primitive	Description		Complexity
 Turn Crank	Simultaneous 2 mps No Force Control Low Accuracy (Constrained)	=	0.56
 Peg-in-the-Hole	Sequential mps Force Control High Accuracy	=	0.50
Peg-out-of-Hole	Single mp Force Control Low Accuracy (Constrained)	=	0.13
 Remove Bolt (Nut)	Simultaneous 2 mps Force Control Low Accuracy (Constrained)	=	0.63
Install Noncaptive Bolt	Simultaneous 2 mps Force Control High Accuracy	=	0.75
 Open Access Door	Simultaneous 2 mps No Force Control Low Accuracy (Constrained)	=	0.56
 Place Module Into Latches	Sequential mps Force Control High Accuracy	=	0.50
 Connect Screw-Type Cable Connectors	Simultaneous 2 mps Force Control High Accuracy	=	0.75
Disconnect	Simultaneous 2 mps Force Control Low Accuracy	=	0.63
Free-Space Module Maneuvering	Sequential mps No Force Control Low Accuracy	=	0.31

Figure 1. Representative task primitives

The three HST batteries are mounted to the inside of the Spacecraft Support Module (SSM) Bay #3 access door (ref. Figure 2). Exchanging the modules requires first releasing the six 7/16" hex J-hook latches (ref. Figure 3) which secure the door, swinging open the door, disconnecting two electrical cables (per module), releasing six J-hook latches securing each module, stowing the old modules on the servicer, and installing new modules by reversing the procedure. The entire operation of exchanging three modules can be decomposed into twenty (20) subtasks, each comprised of task primitives for which complexity values can be assigned (ref. Table 3).

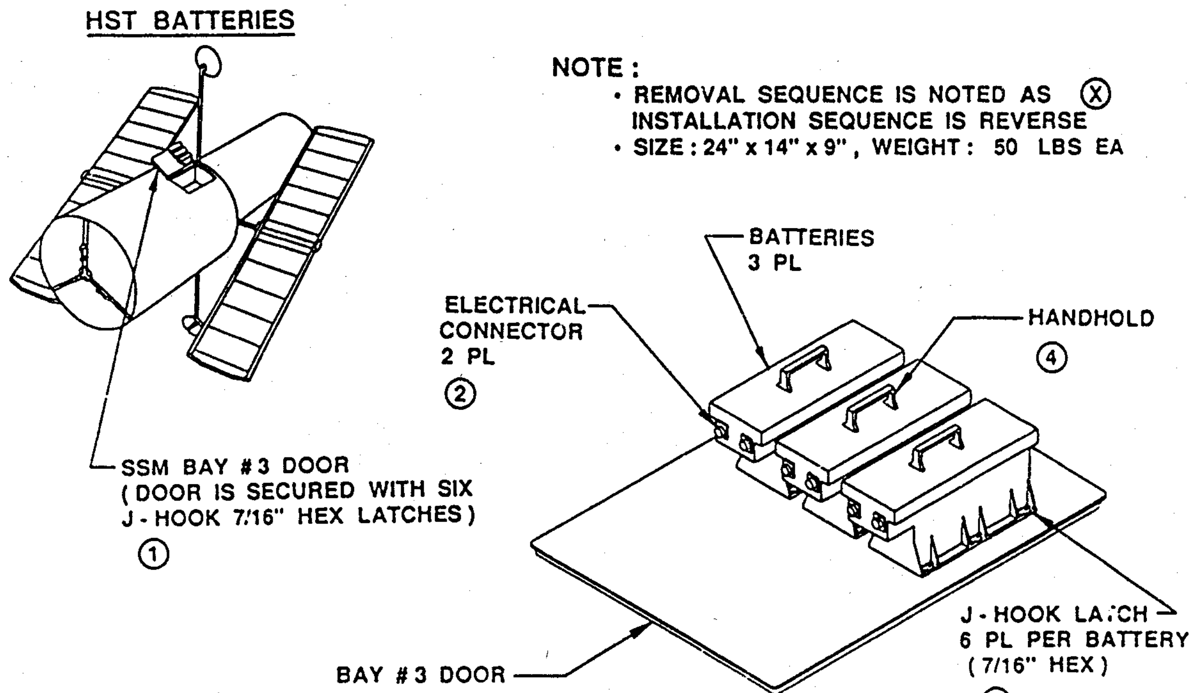


Figure 2. HST battery module exchange task

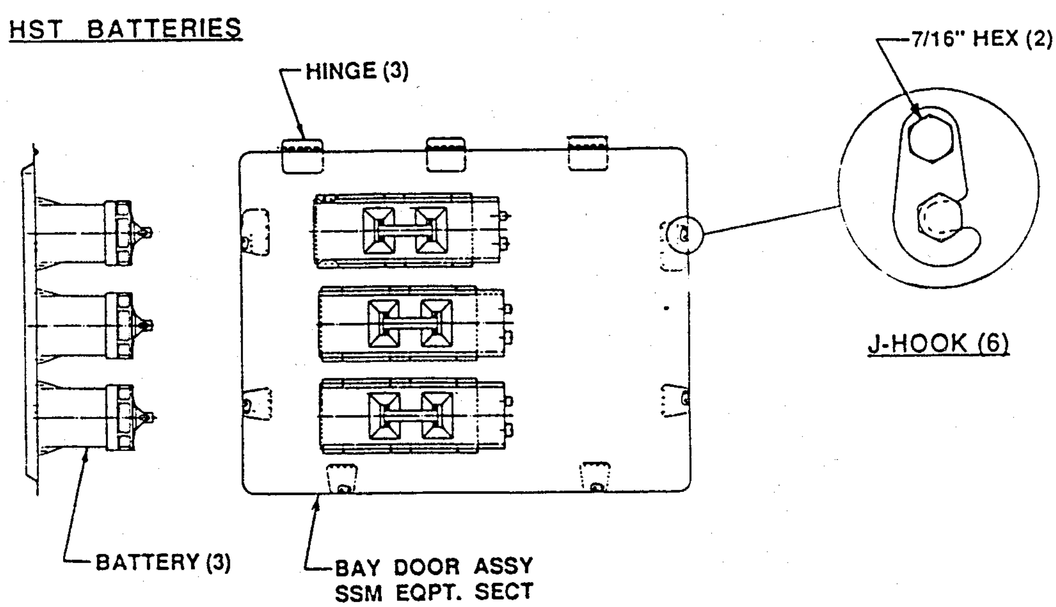


Figure 3. J-hook latch details

SUBTASK	DESCRIPTION	MOTION TYPE	COMPLEXITY
(1)	OPEN ACCESS DOOR		
	• RELEASE J-HOOKS (6) - UNSCREW 7/16" (CAPTIVE) BOLTS (12)	• SIMULT. 2 mps, FC, L	.63 (12)
	• SWING DOOR OPEN	• SIMULT. 2 mps, ~FC, L	.56
(2)	RELEASE OLD MODULE		
	• DISCONNECT CABLES (2)	• SIMULT. 2 mps, FC, L	.63 (2)
	• CONNECT CABLES TO DUMMY RECEPTACLES (2)	• SIMULT. 2 mps, FC, H	.75 (2)
	• RELEASE J-HOOKS (6) - UNSCREW CAPTIVE BOLTS (12)	• SIMULT. 2 mps, FC, L	.63 (12)
(3)	MANEUVER OLD MODULE TO STOWAGE	• SEQUENTIAL mps, ~FC, L (FREE PATH)	.31
(4)	STOW OLD MODULE		
	• PLACE MODULE INTO LATCHES	• SEQUENTIAL mps, FC, H	.50
	• MANUALLY ACTUATE LATCHES - TURN CRANK	• SIMULT. 2 mps, ~FC, L	.56
(5)	RELEASE NEW MODULE		
	• MANUALLY ACTUATE LATCHES - TURN CRANK	• SIMULT. 2 mps, ~FC, L	.56
	• MANEUVER AWAY FROM LATCHES	• SINGLE mp, FC, H	.25
(6)	MANEUVER NEW MODULE TO ACCESS DOOR	• SEQUENTIAL mps, ~FC, L (FREE PATH)	.31
(7)	ATTACH NEW MODULE		
	• PLACE MODULE INTO J-HOOK PROXIMITY	• SEQUENTIAL mps, FC, H	.50
	• FASTEN J-HOOKS (6) - SCREW CAPTIVE BOLTS (12)	• SIMULT. 2 mps, FC, L	.63 (12)
	• DISCONNECT CABLES FROM DUMMY RECEPTACLES (2)	• SIMULT. 2 mps, FC, L	.63 (2)
	• CONNECT CABLES TO NEW MODULE (2)	• SIMULT. 2 mps, FC, H	.75 (12)
(8-13)	REPEAT 2-7 FOR SECOND MODULE	————	
(14-19)	REPEAT 2-7 FOR THIRD MODULE	————	
(20)	CLOSE & SECURE ACCESS DOOR		
	• SWING DOOR CLOSED	• SIMULT. 2 mps, ~FC, L	.56
	• FASTEN J-HOOKS (6) - SCREW CAPTIVE BOLTS (12)	• SIMULT. 2 mps, FC, L	.63 (12)

Table 3. HST battery exchange subtask complexities

To find an effective complexity value for any level of abstraction in the task hierarchy, a weighted average value can be computed. For example, for Subtask #1, the complexity would be found as follows:

[(12)(.63) + 0.56] ÷ 13(OPERATIONS) = 0.625
(UNSCREW J-HOOKS) (SWING DOOR OPEN)

The complexity of the complete operation can be found in a similar manner, as follows:

SUBTASK #1: 0.625

SUBTASK #2: [(.63)(12) + (.63)(2) + (.75)(2)] ÷ 16 = 0.645

SUBTASK #3: 0.310

SUBTASK #4: (.50 + .56) ÷ 2 = 0.530

SUBTASK #5: (.56 + .25) ÷ 2 = 0.405

SUBTASK #6: 0.310

SUBTASK #7: [(.63)(12) + (.63)(2) + (.75)(2) + .50] ÷ 17 = 0.636

SUBTASKS #8-13: [(.645)(16) + .31 + (.530)(2) + (.405)(2) + .31 + (.636)(17)] ÷ 39 = 0.606

SUBTASKS #14-19: 0.606

SUBTASK #20: [(.63)(12) + .56] ÷ 13 = 0.625

BATTERY MODULE EXCHANGE TASK COMPLEXITY:

[(.625)(26) + (.606)(117)] ÷ 143 = 0.609

This average task complexity value for the HST battery exchange mission can then be compared to values computed for other candidate servicing, assembly, and maintenance operations to provide a relative measure of performance difficulty.

CONCLUSIONS AND FUTURE ACTIVITIES

Clearly, the need exists for a generalized, task-based robotic performance metric with which developers of adaptive, EVA-equivalent remote servicers can evaluate candidate systems and assess their capabilities to perform, not only known servicing tasks, but any conceivable task which can be characterized using the basic motion primitives.

This paper presented a very simple, preliminary and untested approach for constructing such a metric, and demonstrated its potential application to a known robotic servicing task candidate. This simplistic approach essentially utilized a linear "fuzzy set" technique for assigning complexity values in lieu of a rigorous analytical description.

The next step in the development will be two-fold:

(1) an attempt to correlate the results of the preliminary approach with empirical lab test data, and

(2) research into analytical techniques that may provide a deterministic basis for assigning complexity values, such as task analysis using screw-theory techniques.

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