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Scheduling robot task performance for a cooperative human and robotic team

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A B S T R A C T

Future space missions will benefit from leveraging the unique capabilities of a cooperative human and robot team for performing operational and exploration activities. This research extends the task allocation and scheduling methodology demonstrated in previous research to characterize the effect of the robotic agent's performance of tasks on overall team performance. Analysis of this parameter in future scheduling projects would provide guidance in selecting a robot design that not only satisfies all operational goals but also contributes to the overall cooperative team performance. The schedules developed meet all of the mission constraints while minimizing overall task list completion time and minimizing the wait time between agents.

1. Introduction

Whether for on-orbit servicing missions or planetary exploration and habitat building, employing a cooperative human and robotic crew in future space missions will enable a larger volume of tasks to be completed. Team members can be combined in various combinations to better utilize their capabilities and skills to create more efficient and diversified operational teams. This involves allocating tasks to provide the most benefit from the partnership, and creating the planning, scheduling, and software interfaces to support these efforts.

There have been several investigations into the utility of human and robot partnerships for space activities. The Ranger Telerobotic Shuttle Experiment was developed to test the ability of an on-orbit dexterous robot to perform servicing activities [1]. Analysis has been performed to assess what roles in team collaboration robotic technology would be best suited to fill [2,3]. Different ways to combine robotic technologies and hardware to aid in the human crew's productivity have been examined [4].

At the present, robotic technologies have been included in space operations to aid in performing tasks that would be difficult for humans to perform. The Space Shuttle's remote manipulator system (RMS) is used to grapple with and maneuver large pieces of equipment (including the Hubble Space Telescope) and as a mobile platform to anchor astronauts. Dextre, the newest addition to the International Space Station's robotic system, is a much smaller robotic agent that provides similar support with the added ability to perform a small set of manipulative activities. Robonaut was specifically designed to perform extra-vehicular activity (EVA) tasks and to serve as a cooperative team agent with a human crew [5,6]. Several generations of Mars rovers have demonstrated success at employing robotic arms for instrument-driven operational tasks in an environment currently uninhabitable by humans.

While robotic technologies have furthered human knowledge of and exploration of space, use of robotics in space has been limited to a few operational scenarios to replace the activities of the human crew. Including robots as

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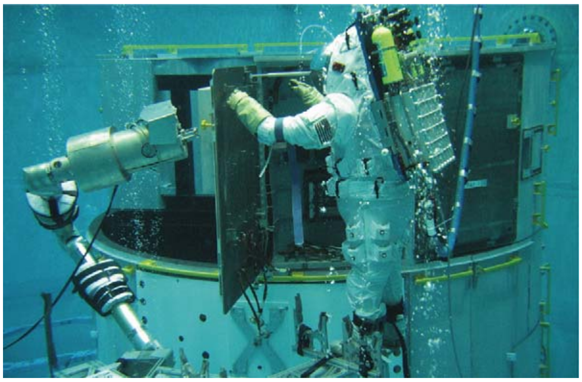


Fig. 1. A cooperative human and robotic team simulating servicing of a Hubble Space Telescope equipment bay in the Neutral Buoyancy Research Facility at the University of Maryland [1].

cooperative agents, working together with the human crew to complete mission tasks as demonstrated in Fig. 1, could augment future space activities.

The research in this paper extends the task allocation and scheduling methodology previously developed to assess the impact of the robotic agent's task performance on the cooperative team's schedule [7]. The methodology takes into consideration real world constraints and precedent constraints to produce pseudo-optimal schedules for a cooperative human and robotic crew. To effectively allocate and schedule mission tasks for a cooperative human and robotic team relies on an accurate characterization of the performance abilities and speeds of the disparate crew.

This task performance research sought to analyze the role of the robot performance parameter (RPP) in the development of a cooperative team schedule. This information can be used to determine a performance bound for the selected robotic agent within its operational capabilities that would reflect the effect that each individual task speed has on the overall team schedule. A robot does not perform every task as quickly as possible, so this level of analysis would seek to match the selected robot's capabilities with the optimal performance required to have it perform and contribute to the development of optimal task performance for the collaborative mission.

Additionally, analysis of the RPP could be used before design selection to influence the rate of task execution, and skill requirements. This would feed preferences derived from an initial scheduling analysis about the role and added benefit of the robotic agent as a crew member on the cooperative team into the design decision.

1.1. Scheduling theory background

There are numerous commercially available scheduling software packages. These tools provide a framework to optimize a list of jobs according to an objective function (frequently minimizing total list completion time) while taking into consideration resource and precedence constraints. Overconstrained problems frequently employ hierarchical task decomposition to break high-level tasks into component pieces that can be individually scheduled. Using optimization software to schedule space operational activities does not work well because the task primitives are highly coupled.

At a high level, this is similar to the crew activity scheduling problem described by Kurtzman [8]. Crew activity scheduling is an overconstrained problem, complicated in space operations by the interdependent nature of the tasks. Batching the primitives into subtasks would address the problem of maintaining precedence constraints during task shuffling, but to prevent over allocation of crew members the entire batch would need to be allocated to a single crew member. Allocating activities based on the subtasks would therefore aid in meeting system constraints at the cost of reduced optimality of the heterogeneous crew.

There are many different kinds of constraints on the crew activity scheduling problem, including differences in crew performance capabilities (dependent on the crew member's physical support to a structure during the tasks), relational, topographical, and precedent constraints between tasks, and time window constraints for nominal EVA operations. Crew availability is treated as a resource and an additional objective of the scheduling is to reduce the wait time of one crew member for another.

1.2. Hubble Space Telescope mission profile

The Hubble Space Telescope Servicing Mission 3A was used as a case study in [7] to demonstrate the scheduling advantages of a cooperative human and robotic team in a space mission application. That case study has been continued in this analysis to establish the role of the RPP in scheduling a cooperative team.

The flight plans from past Hubble Space Telescope servicing missions (HST SMs) provide a detailed test bed from which to examine the effect of various activities and crew performances in space operations. HST was designed with access panels to allow repair of some of the components of the telescope. Some of the servicing tasks require a fine level of dexterity, including manipulation of tethers and electrical connectors. Most of the tasks can be broken down into primitives that require single degree of freedom motion and utilization of a single tool [3]. The latter set of tasks suggest the improvements and extensions to human performance in space by utilizing robots as cooperative team members who could perform these more repetitive tasks, freeing the humans to work on other tasks.

The mission tasks required a broad spectrum of skill capabilities that enabled scheduling analysis for a diverse set of scenarios. Two astronauts were involved in each EVA excursion as can be seen in Fig. 2—one positioned on the end of the Space Shuttle's robotic arm, the remote manipulator system, in the manipulator foot restraint (MFR) which aids in positioning the crew member for servicing activities and one free floater who either tethered to various parts of HST during task performance or who used the portable foot restraint (PFR) to anchor to a worksite. Four days of EVA were planned for this mission.

The 6 h nominal EVA day (including daily setup and closeout of HST worksites) is the primary constraint in the

Fig. 2. Two-human crew replacing the fine guidance sensor on the Hubble Space Telescope (image from nasa.gov photo archives).

number of tasks that can be performed during a servicing mission. Any attempt to reschedule task order is complicated by the need to maintain the sequential constraints between some of the subtasks (e.g., a team member cannot open a door before its securing bolts have been unscrewed) while both minimizing overall human involvement time and minimizing the time one agent has to wait for another.

2. Methodology for scheduling a human–robotic team

The methodology that was developed in [7] for scheduling a cooperative human and robotic team is reviewed here for clarity and logical flow before the extension and analysis of the RPP will be explained. Based on the relative strengths and capabilities of the humans and robots available, the method is capable of creating schedules to minimize astronaut involvement time by stacking astronaut-performed tasks together in the schedule (freeing the astronauts to work on other tasks), and to minimize astronaut workload in the completion of each task.

This scheduling tool has the additional feature of allowing subtasks that are not involved in precedent constraints to be shifted around in the schedule, reordering the tasks from the historical HST SM flight plan. This provides significant improvement in the efficiency of each agent's time in the schedule, while not compromising any mission rules.

2.1. Task decomposition method and application

The initial steps in creating a human and robotic team's schedule follow the process of nominal schedule development. The target set of tasks to be accomplished must be identified and decomposed into task primitives. Following the procedure for the three-tier hierarchical task analysis from the NASA mission timelines [9], each task (ex. instrument replacement) is decomposed into subtasks (ex. retrieval of an instrument), which are further segmented into the primitives (ex. unlatching a door) that define the specific activities needed to complete a given task.

Fig. 3 contains the timeline of scheduled tasks for each of the four EVAs from HST SM3A. The majority of the tasks involved replacement of hardware components on the HST with pieces that had been brought up in the Shuttle's cargo bay. The timeline provides visualization for the number and variety of tasks that could be planned for the two-human crew to complete within the nominal EVA day time window.

Both of the humans were obligated during all of the tasks in varying capacities. Generally the astronaut positioned by the RMS (called EVA2) performed hardware maneuvering and use of the power tools while the other astronaut (EVA1) disconnected securing straps and connectors from hardware and provided supporting aid when needed. Replacement units were transferred from one astronaut to another. Both astronauts were used to carefully position instruments like the fine guidance sensor (FGS) along the guide rails for insertion and installation into HST. Only a few of the subtasks involved with this mission required manipulation of electrical connectors or harnesses.

2.1.1. EVA task data sources

There was significant deviation between the predicted flight data (which was used for developing the NASA timelines and mission schedules) and actual flight data from SM3A. The SM3A case study in [7] relied on the planned EVA task times for the scheduling analysis. Subsequent to that work, this author performed a peripheral analysis to compare the accuracy and completeness of the flight data sources (flight log [10] and flight footage [11]) and of the planned preflight estimates (obtained from the EVA Checklist [9]). The procedure and results are here described, and the decision to continue use of the preflight subtask estimates explained.

The flight logs recorded all voice communication between the EVA crew, the intra-vehicular activity crew (IVA) inside of the Space Shuttle controlling the RMS, and ground personnel in mission control. The flight logs contain the time of the voice communication (recorded in GMT to the thousandth of a second), a description of the event, the individual who made the communication, the subtask category of the primitive being recorded, and a flag to note if an anomaly occurred.

The flight footage was recorded from several camera views during the mission and was used by mission control to monitor mission progress. Each frame of the flight footage had a mission duration time-stamp superimposed on it.

For this analysis, task duration times were manually recorded at the primitive level from both the flight log and the flight footage for the FGS changeout from SM3A EVA day 2. This changeout task contained 140 task primitives and was estimated in the preflight plan to last for 2 h and 40 min. Each of the primary datasets for this task was compared in order to determine which would be most beneficial to use during an attempt to reschedule the mission for a cooperative human and robotic crew.

2.1.2. Analysis of flight datasets

There were several factors that influenced the completeness of the datasets. Astronauts were trained to minimize their dependence on the communication audio loop. To this extent, the astronauts frequently relayed confirmation that they had completed a set of tasks rather than the individual primitives. During the FGS-2R installation subtask, EVA1

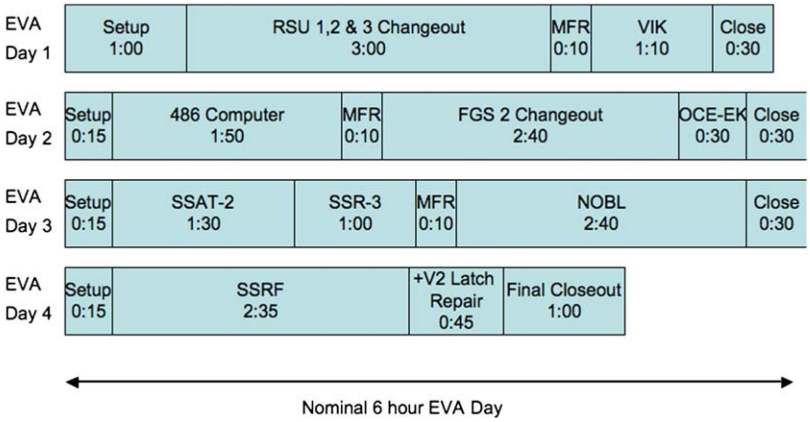


Fig. 3. HST SM3A EVA task timeline as represented in the EVA Checklists [7].

confirmed that he had retrieved cables, installed a ground strap, completed four identical electrical connector primitives, and removed a tether, all with a single voice communication rather than confirming each one individually. The time stamps were used to generate a time window during which all of these primitives were completed, but further subdividing of this time interval was not possible from the flight log.

During maneuvering for job performance, the astronauts regularly occluded the camera views for the flight footage of the activity they were performing. The flight log reinforced the flight footage during portions when the audio component of the footage was difficult to hear clearly.

The flight footage proved to be a substantial resource for explaining the affect that anomalies had on the preflight task plan. When an anomaly was encountered that required advice from mission control, the discussion that followed about alternatives caused significant sliding in the schedule. The FGS-2R subtask that had been estimated to have a 20 min duration occupied 49 min in the EVA day during the actual servicing mission. The actual in-flight duration of this subtask was more than double the preflight estimate due to difficulty encountered with inserting the new hardware into HST and concern about how to remedy the situation without damaging the hardware. There were five observed anomalies during the FGS changeout task that contributed to the task requiring over 4 h to complete rather than the estimated 2 h and 40 min from the preflight plan.

Similar instances of the same primitives performed by the same astronaut were identified in the schedule for this data analysis and these durations extrapolated to fill in the holes. The data entries were flagged to note that they were extrapolated from the primary data. Performing this repair of the datasets filled in 36% of the time duration for the flown dataset. Combining the data from both the flight log and the flight footage still resulted in 45% of the time being unaccounted for in the dataset.

2.1.3. Discussion of primary dataset selection

Although the level of detail that could be obtained from the post-flight data analysis was of higher resolution than the preflight subtask estimates, the incompleteness of the dataset would feed uncertainty into the scheduling efforts. The weighting of anomalies on the performance data would add additional variables to the scheduling efforts.

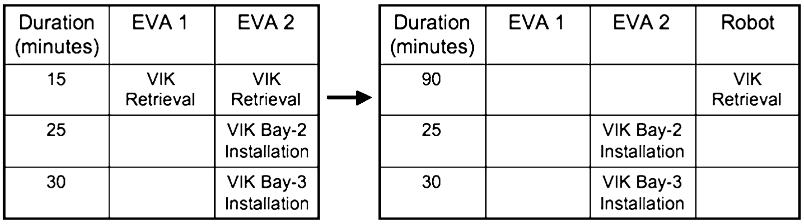
The primary source of deviation between the planned preflight estimates and the flight data was due to anomalies on-orbit. It was determined that the time estimates with which the NASA mission timelines had been created and flown should be used in this analysis for consistency and to facilitate comparison between the NASA flight plans and the cooperative human and robotic schedules.

A planned estimate of crew performance time for each subtask was obtained from the EVA Checklist for SM3A [9]. These times were based on Neutral Buoyancy Lab testing results and simulations [12]. The checklist contains a detailed listing of the task primitives necessary to accomplish each of the subtasks, but the duration data is only represented at the subtask level, rounded to the nearest 5-min increment.

2.2. Team definition methodology and application

Adding a robot to the crew for activity scheduling creates additional complexity due to the potential implications of the various time scales involved in task performance. The capabilities of each crew member must at this point be clearly defined, including definition of the robotic agent's skills and tools.

The team selection and description of capabilities from [7] was used in this research. The schedules developed using the task allocation methodology are dependent on individual crew member capabilities and task performance times. Any robotic agent selected to participate in mission activities would have specific capabilities and limitations that would factor into both the task allocation and the resulting schedules. Similar to [7], this research sought to quantify the impact of a generic dexterous robot, independent of specific design configuration, as a supplement to the standard two-human EVA crew for on-orbit servicing activities. The primary features that characterized the generic robot are reiterated here to present the assumptions that the task



Duration (minutes)	EVA 1	EVA 2
15	VIK Retrieval	VIK Retrieval
25		VIK Bay-2 Installation
30		VIK Bay-3 Installation

Duration (minutes)	EVA 1	EVA 2	Robot
90			VIK Retrieval
25		VIK Bay-2 Installation	
30		VIK Bay-3 Installation	

Fig. 4. Subtask reallocation for the VIK replacement task from HST SM3A to utilize a robot in the crew.

allocation and, subsequently, the affect of the RPP on the cooperative team's schedule are dependent on.

Similar to the design of Robonaut, the robot was assumed to be capable of configuring its own tools, to have all end effectors necessary to complete the jobs assigned to it, and to be capable of using EVA hardware interfaces (like handholds) and tools. The robot was assumed capable of all force/torque application primitives (including use of EVA tools), hardware handoff and translation, and visual inspection primitives (through either feedback to a controller or autonomous recognition capabilities). It was further assumed to have at least two independently controllable dexterous arms with approximately the same capabilities and reach as a human for sizing around the tasks.

Although the characterization of the robot's mobility and positioning system will be dependent on the specific robot configuration selected, for the purposes of this study it was assumed that the robot's positioning mechanism would be independent of the human crew's positioning systems. The robot could be designed with a positioning arm in addition to its assumed dexterous arms [5]. This independence would allow the robot to be added to the human crew's task performance rather than occupying one of the required human positioning aids. The robot will not need to use either the MFR or the PFR to complete its portion of the mission tasks.

To reduce the dependence of the scheduling model on a specific set of robotic technologies, a flight rule was established in [7] that if the robot was active in the same workspace as a human, it would only be doing tasks in support of and that relate directly to the tasks the human was performing (including passing the human hardware), rather than independently performing tasks. A HST flight rule had also been extended to enable the robotic agent to continue servicing activities outside of the human EVA day, when the human crew was no longer on-site. Both of these flight rules continued their relevance to the task performance research and were incorporated into this analysis.

It was hypothesized that the robotic agent's primary contribution would be in the preparation and closeout of the human task sites in absence of the human crew. With the daily setup and takedown allocated to the robot, its daily task involvement reduced the required human time for each EVA day by 55 min for setup and 60 min for cleanup of the worksite.

2.3. Task allocation for a cooperative human and robotic team

The methodology guides the initial task allocation for a mission based solely on agent skill capabilities. Each task primitive should be analyzed to determine whether the robotic agent is capable of performing it. Primitives that the robotic agent is unable to perform should be identified and allocated to the human crew. Initially, the remaining task primitives should be allocated to the robotic agent.

Each subtask is then assessed to determine whether the robotic agent can complete all of the required primitives. If the robot is capable of performing all of the primitives within a subtask, then the subtask is allocated to the robot. If there are primitives that the robot is unable to perform, then the entire subtask is reallocated to the human crew.

Task allocation based on the predicted performance capabilities of the combined two-human and robotic crew was performed at the subtask level for all of the HST SM3A tasks. Due to the fine level of manipulation and complex motion required, it was judged that humans should service electrical connectors, harnesses, and tethers. After determining which subtasks must be performed by humans, the next step in building a cooperative schedule was to assign all remaining tasks to the robot agent.

The majority of subtasks in space applications must be performed sequentially due to precedence constraints. In this methodology, subtasks that are not involved in precedence constraints are moved in the schedule to group time periods of human activity, shortening the human crew's involvement time in a given task. To ensure task quality and completion, preemption is not allowed. A subtask must be completed before the crew member can move to another subtask.

Once the initial task allocation has been completed, a schedule can be developed. The strategy used in assigning subtasks between the human crew and the robot has a significant impact on the efficiency of the schedules created. Each candidate set of allocated tasks can be used to derive the most advantageous global schedule for that case. This allows the selection of the task allocation strategy which best optimizes the overall mission objectives, since each candidate allocation case is characterized by its best-performing schedule.

Fig. 4 depicts the NASA flight plan subtask allocation and scheduling between the two-human crew members for the voltage instrument kit (VIK) replacement task in the left table. The chart to the right demonstrates the reallocation of the VIK task to the three-agent crew. The hardware retrieval subtask was reallocated to the robot in this schedule.

There are two important details to note from Fig. 4. First, the task allocation strategy removed the need to involve EVA

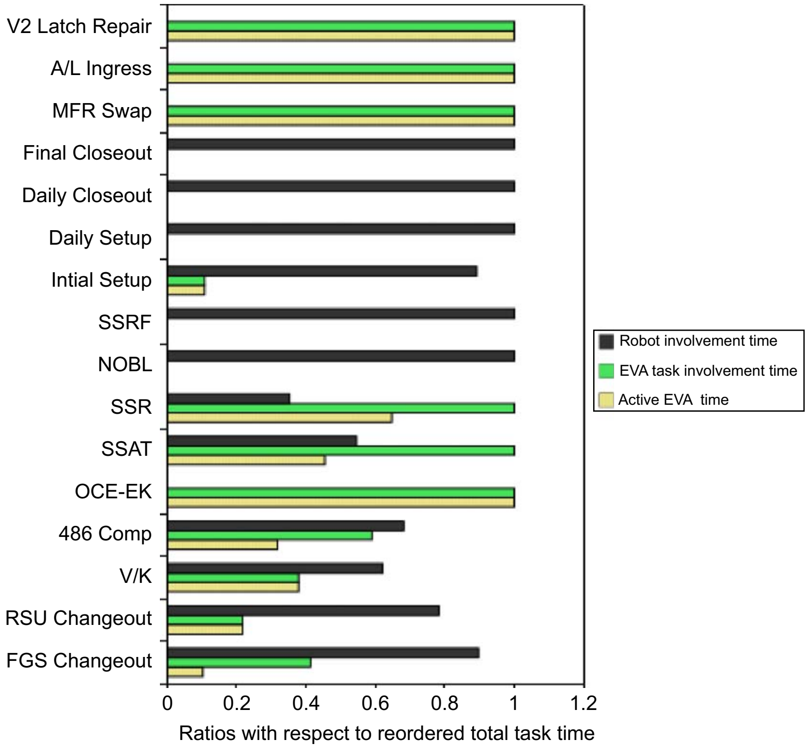


Fig. 5. Task allocation of the HST SM3A tasks for the cooperative team [7].

1 in the VIK replacement task. Secondly, a nominal RPP of 3 was used when generating the task schedule in [7]. Because the astronaut was only involved after the robot finished its activities, the total human crew active time would have been unchanged if a different value had been used. The total human crew active time was reduced from the NASA mission timeline by 15 min, a 20% reduction.

Fig. 5 depicts the results of the task allocation for each SM3A task. It should be noted that several of the mission tasks were entirely allocated to the human crew, and that several were allocated entirely to the robot.

After the subtask-level task allocation analysis, it was noted that 22% of the HST SM3A mission subtasks needed to be performed by the human crew. For the task allocation strategy specified, this was the minimum solution for EVA time for the mission task profile. The robotic agent defined for this paper was able to aid the human crew in 78% of the mission subtasks and participated in 75% of the tasks completed during HST SM3A. 31% of the mission tasks were reallocated entirely to the robot, freeing the human from involvement in the given task.

One of the most significant results from [7] was that all of the tasks that had been performed during HST SM3A could be completed in half the active EVA time than during the NASA mission by including the generic robot in the crew. Had a cooperative human and robotic team been employed on the mission as defined in this paper, twice the volume of tasks could have been accomplished during the EVA time of HST SM3A.

3. Robot performance parameter

The primary criteria used to assess the value of a cooperative team over the standard two-human crew is the reduction in active human time (representing a specialization of the human crew's activities) and the time that each human crew member must wait for the robotic agent to perform its subtasks (a check on the efficiency of the schedule).

The time that the human crew wait for the robot to complete a precedence constrained subtask is the difference between the human involvement time and human active time within a task. This difference represents the time that the human crew was present on-site but not involved in a subtask. It is the human crew's wait time that would prove to be the critical factor in determining an acceptable RPP for the activities interspersed with those of the human crew.

The present analysis examines the extent that precedent constraints between subtasks and primitives create intervals of wait time for the human crew of a cooperative team. These wait time intervals can only be influenced by agent performance speed or reallocation of tasks to different agents. In general, if the wait time is longer than the human performance time of the given subtask, the subtask should be reallocated to the human crew.

3.1. Role of the robot performance parameter

It is at this point in the scheduling methodology that the robot performance parameter can be seen to have a distinct impact on the human schedule. In [7], a single value was selected as a placeholder to acknowledge that a generic robotic agent's task performance rate would differ from that of the human crew and that this difference would have an impact on the development process for a collaborative schedule.

The remainder of this paper seeks to more closely examine the effect of the robot's task performance. It should be noted that the task allocation within the methodology was performed entirely based on each agent's physical capabilities. The RPP describes how well or how quickly the robot performs these tasks in comparison to the activities of the human crew.

A robot's subtask performance will be dependent on the specific operating mode selected for each individual task. All agents do not necessarily perform each task at the fastest speed possible. There are several other factors that often result in a robot operating at speeds well within its absolute ability.

Testing with telerobotic systems performing satellite servicing tasks has shown that robot performance varies from human performance by time multipliers as low as 1.25 and as high as 6 [13]. Smaller multipliers produce better-matched teams of agents (similar to scheduling for traditional human-only operations). Larger multipliers produce such disparate performance times that the utility of enforcing cooperative operations in scenarios would be questioned.

In this analysis, a variety of RPP values were used ranging from 0.25 to 6. The range derived from experimental data [13] was expanded to include robots performing tasks faster than their human counterparts would be able to for completion of the data set. RPP values below 1 are technically difficult to achieve in the design of a robotic system for anything but a very narrow task set. A highly selective application of a well-developed tool is the example of a power drill tool. It can perform a task much faster than a human but has very limited application.

For most space applications, robotic technology has not yet progressed to allow a robotic agent to perform a wide variety of tasks at a rate similar to that of the human crew. The cumulative robot performance of individual task primitives becomes the time critical path during scheduling for a disparate crew. Slower robots would be expected to elongate human wait time in the cooperative schedules.

3.1.1. *Role of the third agent*

It is intuitive that adding a third agent to the servicing team would create schedule benefits by reducing the workload of the original two-human crew through parallel execution of servicing tasks. The role and level of contribution of this third agent depends on the proportion of mission tasks that the third agent has the capabilities to perform, the interdependence of this subset of tasks to those performed by the other crew members, and the rate of task performance and completion of the subset.

In the specific case of an RPP equal to 1, the third agent can be considered as a third human on the crew with restricted task capabilities. To isolate the effect of the RPP on the three agent schedules developed, the flight rules that limited simultaneous task diversity within a cooperative workspace still applied. In particular, the third human was restricted to working on the same task as the other two humans if all three were within the same workspace. A new baseline was established to compare the RPP-varying schedules with a timeline that had been scheduled for a restricted three-human crew.

This research facilitates the ability to more accurately predict how much the human crew's wait time could be reduced by various robotic configurations. Analysis of the effect of the RPP on the cooperative schedule provides framework for using human time window constraints to back out the required robot performance time to maintain an efficient cooperative schedule. This in turn can be used to set robot design requirements.

4. RPP analysis

For the task allocation strategy employed, Figs. 6–9 demonstrate the effect of using a range of RPPs on each agent's timeline within the cooperative schedule. These figures represent graphical timelines that demonstrate when the three agents were actively engaged in each EVA day's activities for the range of RPP values. The increasing length of the time gaps in the human agents' timelines demonstrate the sliding of the timelines from increasing RPP values lengthening these wait intervals. As had been anticipated, the robot's activities increase in length (as can be seen by the lengthening of the red lines) while the human periods of activity remain constant in length. In the human crew's timelines it is the periods of inactivity that grow in length as the RPP value is increased.

The human crew was only involved in one subtask during EVA day 4. The result on that day's cooperative timeline can be seen in Fig. 9. The total length of that day's activities increases with an increasing RPP value, but the human active time and the length of the human involvement in the day's tasks remains unchanged by the RPP value. This is a special case because due to the task allocation strategy that had been selected, the robotic agent was capable of performing all of the other subtasks for that mission day.

Figs. 10 and 11 demonstrate the effect of increasing the RPP on each agent's proportional participation in each mission day. The human crew's active time, the robot's active time, and the human crew's inactive time are all shown as ratios to the total length of the day's activities. As the RPP value increases, the robot's activities dominate the timeline, marginalizing the participation of the human crew. The gap between the EVA active time and EVA day duration curves represents the fraction of the human crew's day that is spent inactive.

It should be noted, however, that although the fraction of each day's activities that the human crew participates in drops with increasing RPP, this value remains above 0. The effect of this fraction is to continue to increase the total human crew's involvement time because the total length of each day's activities increases with increasing RPP. To reduce this involvement time, the smallest possible RPP should be used.

The time windows of human crew inactivity seen in Fig. 12 were due to the need to remain on-site to perform a subsequent precedence constrained task. As had been seen

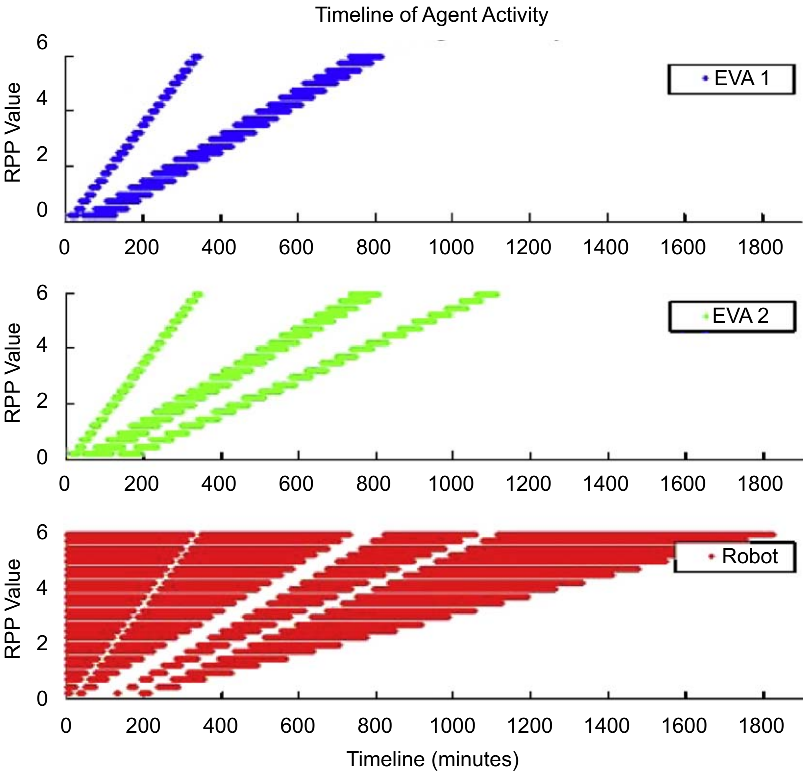


Fig. 6. Effect of RPP value on agent timelines for EVA day 1.

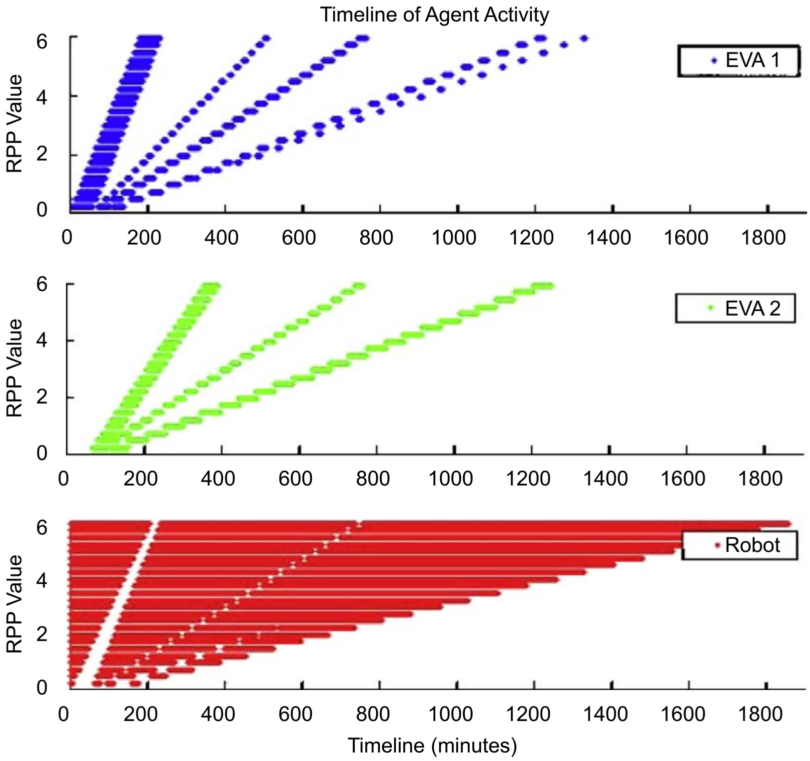


Fig. 7. Effect of RPP value on agent timelines for EVA day 2.

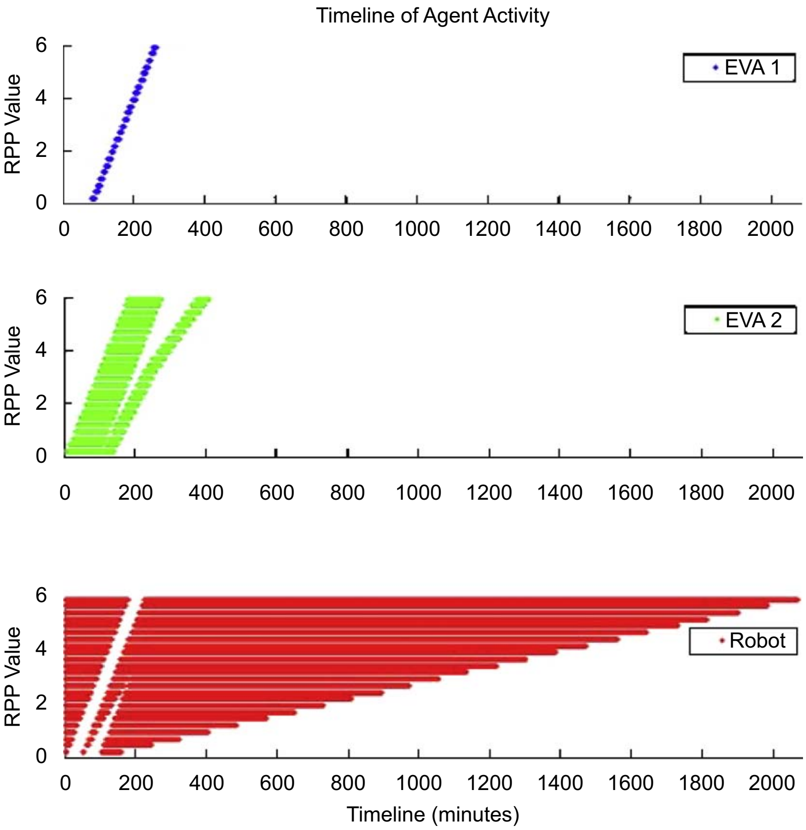


Fig. 8. Effect of RPP value on agent timelines for EVA day 3.

in Figs. 6–9, these wait time intervals increased in duration with an increasing RPP value.

Fig. 12 details the increase in the human crew's inactive time for each EVA day as the RPP value was increased. The smallest inactive time was 5 min for EVA2 during day 3 activities with an RPP = 0.25 and the largest inactive time was 1045 min for EVA2 on day 2 at an RPP = 6. It is interesting to note that both of the extreme values in the figure were data points for EVA2. This is an indication that EVA2's activity data was much more interdependent on the RPP value than EVA1's.

EVA1 consistently had a longer wait time than EVA2 for each RPP value. This was due to the task allocation based on agent capabilities, including each agent's positioning mechanism. While EVA2 was rigidly attached to the RMS for all activities, EVA1 was attached with a flexible tether or portable foot restraint to each worksite. EVA2 performed more mission activities than EVA1 and alternated task performance with the robot more frequently.

The incremental increase of the human crew's inactive time can be interpreted as the cost–benefit function that had been sought. As seen in Fig. 13, this provides a quantitative method to gauge the worth of decreasing an RPP value and seeing the effect in reducing human wait time.

EVA day 4 is notably absent from both Figs. 13 and 14. This is due to the result seen in Fig. 9, that the human involvement in that day's activities for the cooperative team was independent of the RPP value used for the robot. There was therefore no cost or benefit to the human crew for EVA day 4 to have a different RPP value.

The marginal decrease in human involvement time that occurs when the RPP value slides above 2 in Fig. 12 demonstrates an interesting result of the cost–benefit analysis—at a certain point, an increased RPP does not significantly affect the proportion of the EVA day that the human crew is idle. It should be remembered, however, that the total quantity of human involvement time continues to increase for an increasing RPP value.

Fig. 14 gives the perspective of the incremental increase in the length of the EVA day in comparison to an RPP value of 1. There is a huge scheduling benefit to pushing RPP below 1—the proportion of each EVA day that the human crew is active increases because the wait time for the robotic agent is drastically reduced. This scenario would require development of a robotic agent that could perform a wide range of task primitives at a rate faster than a human.

From Fig. 14 it can be seen that increasing the RPP from 1 to 2 increases the total length of the EVA day by 200 min. This clearly highlights that although the EVA portion of the total day length decreases as the RPP value increases, the total increase in EVA day length can quickly reach unacceptable levels.

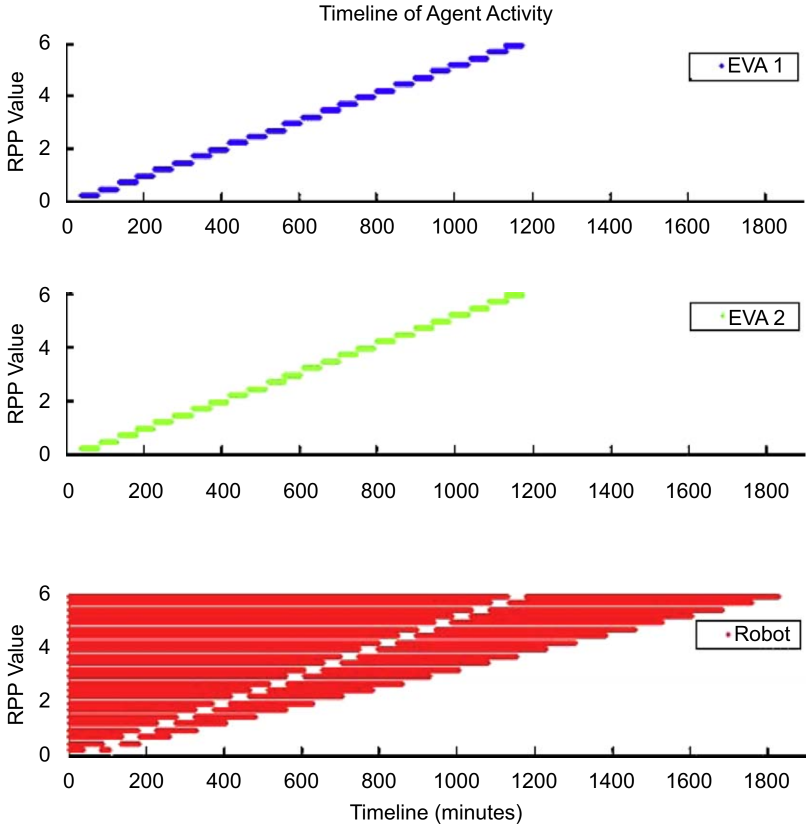


Fig. 9. Effect of RPP value on agent timelines for EVA day 4.

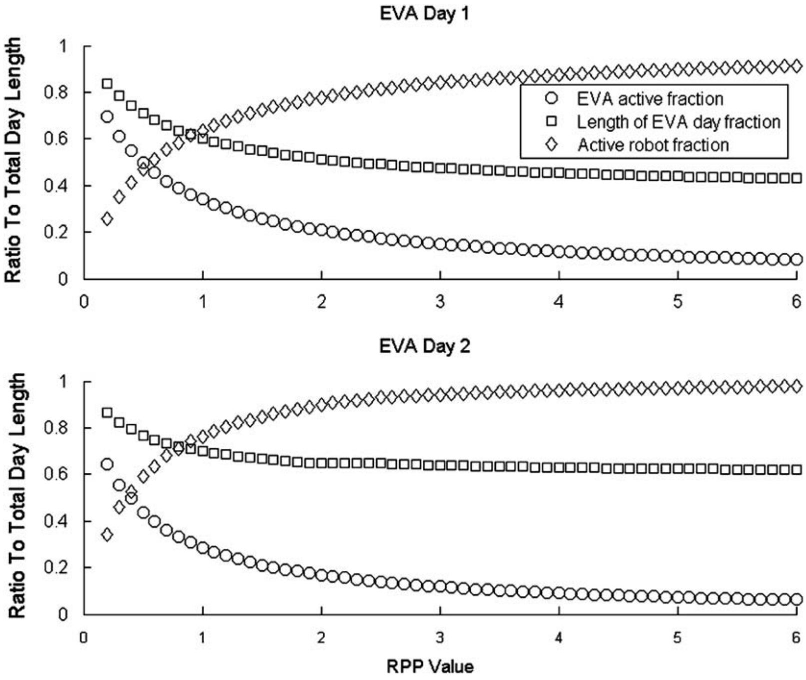


Fig. 10. Effect of RPP value on ratio of agent participation in days 1 and 2 activities.

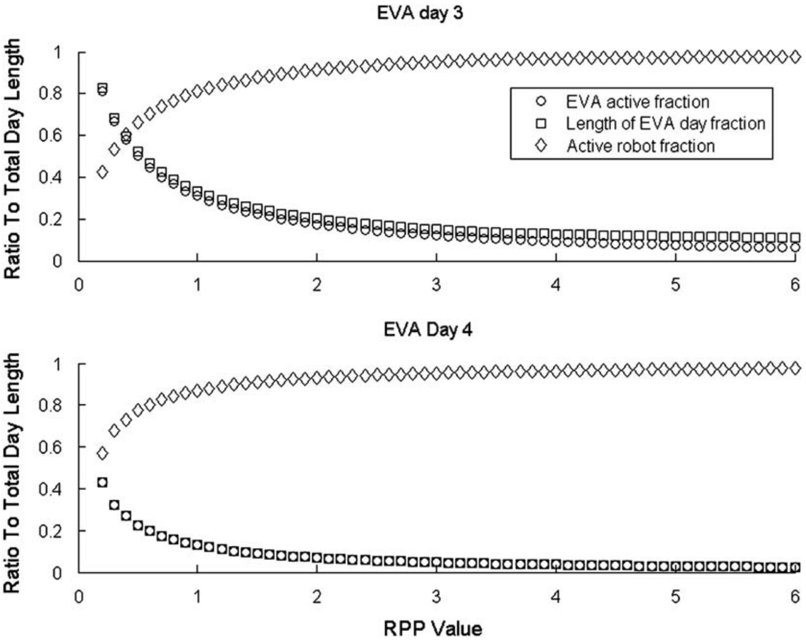


Fig. 11. Effect of RPP value on ratio of agent participation in days 3 and 4 activities.

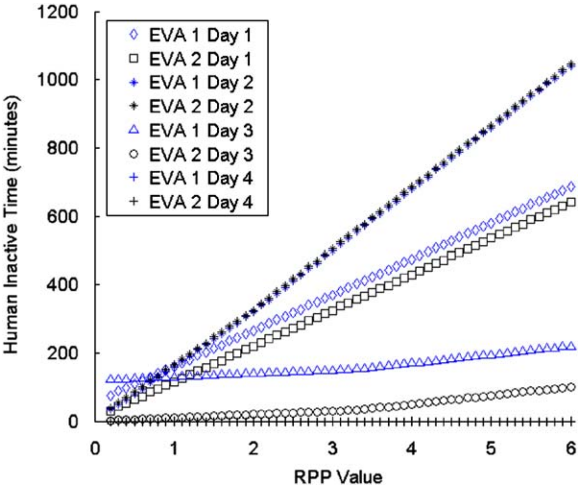


Fig. 12. Effect of the increasing RPP value on the human crew's inactive time.

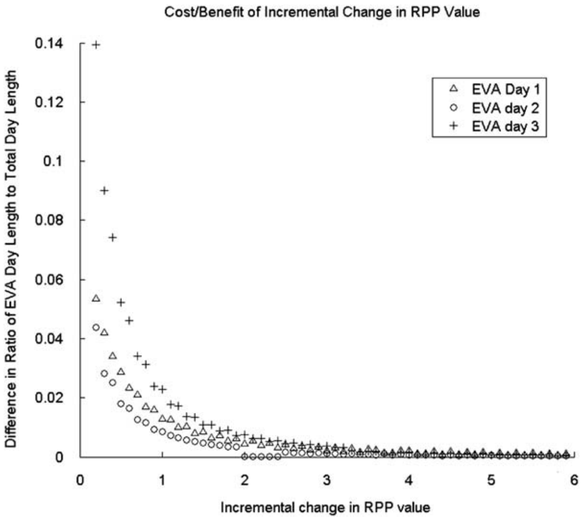


Fig. 13. Cost benefit ratio for incremental increase in RPP.

As seen in Fig. 14, the slopes of the three EVA day curves depict a markedly different sensitivity response to varying the RPP. The slope for EVA day 3 suggests that an incremental change in the RPP value would have a much smaller influence on the human wait time. A slower RPP value could be used to better optimize or reduce the cost of the robot itself without causing a significant change to the cooperative schedule. The opposite was the case for EVA day 2, where there was a strong influence between a change in the RPP value and the corresponding change in the human wait time. Although this response variation is a characteristic of the task allocation for each of the days, this type of variation across mission days and activities should be taken into consideration when assessing the effect that an RPP change will make on the overall schedule.

5. Discussion

The human crew's wait time can be reduced by three different methods, depending on the flexibility of the scheduling. Robot tasks that are causing extended periods of human wait time because of precedence constraints between subtasks could be reassigned to the human crew to perform. The human crew would not be sitting idly during these time periods and would complete the tasks in a shorter period of time, benefiting the total mission schedule at the expense of increasing their active time within an EVA day.

Additionally, these large windows of unoccupied human time suggest that sending the humans to perform other subtasks while waiting for the robot to complete a subtask could increase the schedule benefits. This would be taking advantage of including a third agent by increasing the volume of tasks that would be completed. The third option would be an a priori design decision to select a different robot that could perform the task with a lower RPP value to better accommodate an efficient cooperative schedule.

For a given allocation of tasks and agent capabilities, the influence of the RPP on the human crew's schedule can be combined with other optimization criteria to create bounds on the robot performance. Fig. 15 shows the increasing length of the EVA day (the human crew's involvement time) as a function of the increasing RPP value. The NASA flight rule limiting the planning of a nominal EVA day to 6 h in duration can be seen as the horizontal line in this figure. EVA days 3 and 4 do not have difficulty meeting this constraint, but for EVA day 2 to meet this constraint, the RPP for that day must be less than 1.5 (at least for the subtasks interspersed with the human crew's). Applying this constraint to the cooperative schedule, it is apparent that an upper bound must be applied to the robot performance to meet this constraint.

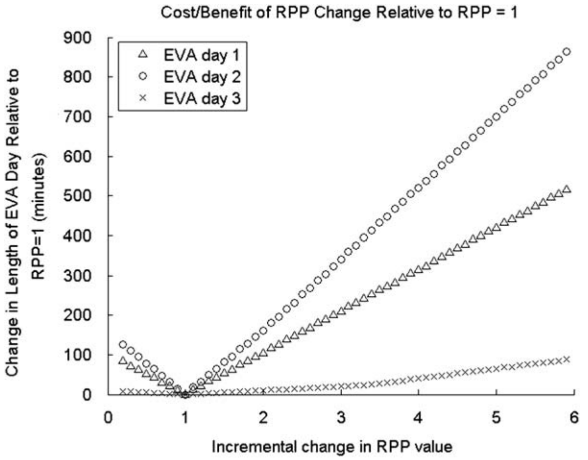


Fig. 14. Cost benefit for incremental increase of RPP above a value of 1 (in minutes).

This result has interesting implications for robot design and selection for future missions. The allocation of tasks will be dependent on the skills and physical capabilities of all of the agents involved. Once a robot has been selected for a mission, all tasks that the robot cannot do will be allocated to the humans. Other optimizing criteria can factor into deciding which of the capable agents will perform each subtask during the mission. If a selected robot design could perform its tasks with an RPP less than or equal to 1.5, then it would be a productive crew member for the HST SM3A rescheduled mission.

The design determining tasks for selecting the RPP would be the 78% of mission subtasks and 75% of mission tasks that were cooperatively allocated to both the human and the robotic agent in the crew because the precedence constrained subtasks created intervals of wait time for the human crew [7].

5.1. Effect of an alternative robotic agent

Due to technical or budgetary constraints, a particular skill set for the robotic agent may not be available for a mission. To facilitate a relative comparison between the utility

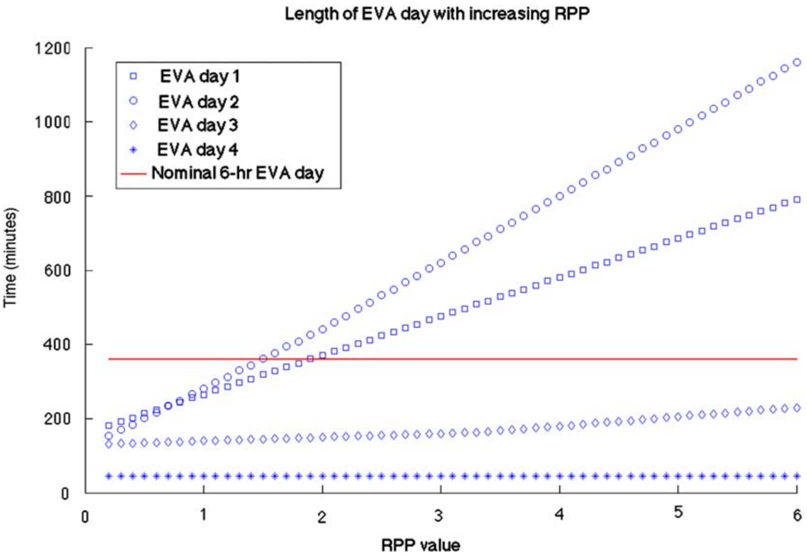


Fig. 15. EVA time window constraint limits range of acceptable RPP values.

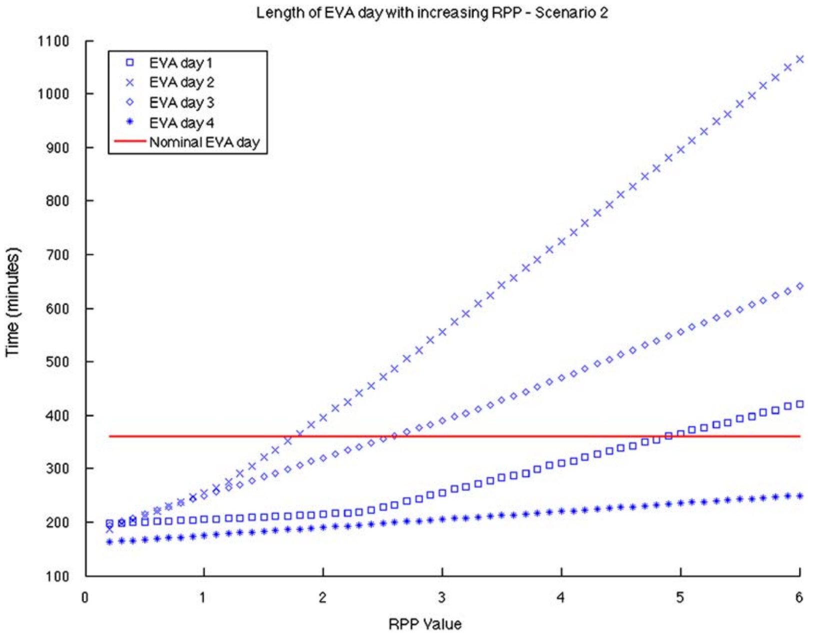


Fig. 16. EVA time window constraint limits for scenario 2.

of various robotic technologies on the overall mission profile, an additional robotic concept was examined.

This scenario included a robotic agent on the cooperative human and robotic team that had a more limited range of motor skills than the robot previously considered. This type of robot can pinch and grasp objects and serve as a hardware maneuvering and retrieval platform. Unlike the generic robot discussed previously, this alternate robot concept is incapable of performing task primitives requiring finger dexterity or any additional tools or end effectors. Under this concept definition, the robot was precluded from most of the hardware installation subtasks.

This scenario was selected because the robot's activities, while constrained to a smaller task set, were still intermixed with the tasks allocated to the human crew. This provided an additional cooperative team scenario with a realistically defined robotic agent to compare the effect of the RPP value on the human crew's schedule. The task allocation methodology from [7] was employed to determine which tasks each of the three agents in the new scenario should perform and the scheduling tool rearranged the subtasks to reduce the human crew's wait time (while observing precedence constraints).

Fig. 16 shows the total length of each of the human crew's EVA days under the second scenario's new task allocation and scheduling analysis. Similar to Fig. 15, it can be seen that the human crew's day lengthens with increasing RPP values. The horizontal line demarcates the nominal 6 h EVA day time constraint that limits the amount of time astronauts can be involved in each day's activities.

It is apparent from Figs. 15 and 16 that EVA day 2 is the RPP-limiting case in both scenarios. This is due to the fact that the human crew and robot alternate subtask performance several times within the day, making human involvement time dependent on robot performance time. To satisfy the time constraint, the robot in scenario 2 would need an overall RPP less than or equal to 1.75. At that RPP value, the human crew would not violate the time constraint on any of the EVA days.

It is interesting to note that a slightly larger RPP value could be used in this scenario than in the previous (which required a value less than 1.5) and still meet the nominal EVA day time constraint. This allows a little more flexibility in the design requirements for the robotic agent, slightly relaxing the robot's required task performance rates to be an efficient cooperative team member.

Fig. 17 compares the two different scenarios for the three agent cooperative team. The human crew's active time, total involvement time (represented as the EVA day length), and the robot's active time were each summed across all of the EVA days to represent the total amount of time as a function of total task list completion time. As was anticipated, reducing the subset of tasks performed by the robot in scenario 2 not only increased the proportion of the tasks completed by the human crew, but also increased the proportion of time that the human crew was on-site waiting for the robot to complete a precedence constrained task (seen in the figure as the difference between the EVA day length and the EVA active time).

The cooperative schedule resulting from scenario 2 necessitated the human crew to be involved in 10% more of the total extra-vehicular activity mission tasks than in scenario 1. In scenario 1, the human crew was inactive for 50% of its total involvement in the EVA days. In scenario 2, however, the human crew was only inactive for 40% of its total involvement time. Although the human crew's workload was

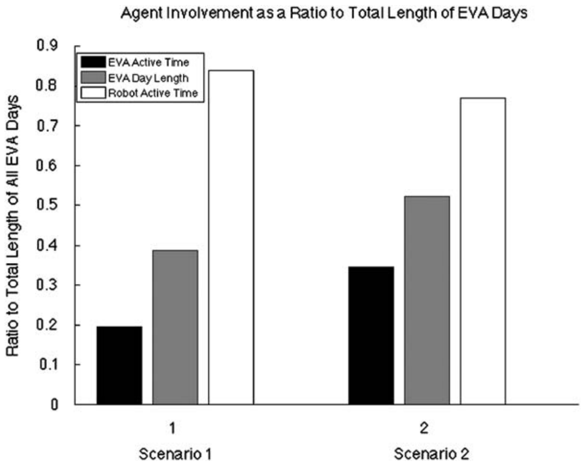


Fig. 17. Comparison of agent involvement in the two scenarios.

larger in scenario 2, the human crew was employed more efficiently because they were idle on-site for a smaller fraction of time.

The effect of the different skill sets and RPP used in the two scenarios on the human crew's efficiency demonstrates a scheduling and efficiency trade-off between distributing the task workload and minimizing both the human crew's involvement time and the mission completion time. In future applications, other factors would be incorporated into the decision including the availability of specific robotic technology and the potential to further specialize the tasks of the human crew.

5.2. Creating heterogeneous multi-agent teams

An extension of the cooperative team analysis would involve multiple robots with different skill sets and performance abilities. It would be anticipated that increasing the number of agents participating in a cooperative team would further distribute the workload, decreasing the overall mission completion time and allowing task specialization for the various crew members. Three cases of ascending heterogeneity will be briefly considered.

The first case considered two identical robots working cooperatively with the two-human crew. The robots would have identical skill sets and performance abilities (RPP values). Allocating tasks between them and the human crew would be aimed at minimizing the human crew's involvement in the HST SM3A mission tasks while distributing the workload between the two robots. The use of an additional robot would be to roughly halve the robot's task list completion time (although workspace interference its potential to reduce task speed would need to be considered).

In the second case, two robots with identical skill set but with different RPP values would be included on the cooperative team. The difference in task performance speed could be accounted for as a different version or design of the robots. The robots could perform the same set of task primitives, but at different rates. The third case would involve two robots that have different skill sets and different RPPs. Efficiently coordinating all of the team members for both of these cases will require balancing the physical workload given to each agent to expedite completion of the task list while minimizing the amount of time agents wait for each other.

Several modifications would need to be made to the task allocation and scheduling strategy for these types of scenarios. A method to determine which physically capable robot (assuming several options are available) should be utilized for a given task would need to be implemented. Initially allocating the task to the robot that performs the subtask fastest (to minimize the total mission completion time) could create a bottleneck in the schedule or result in underutilizing slower performing robots. This could be alleviated by altering the task allocation and scheduling tools. The scheduling tool would need to seek the multi-objective optimization of what quickly becomes a traveling salesman problem: balancing the workload of the robots to increase their on-site efficiency (and while minimizing the amount of time that the human crew must wait for the robotic crew to complete precedence constrained tasks) while taking into consideration the robots' disparate characteristics and mitigating workspace interference (which would require spatial modeling and planning), and minimizing travel between work sites (giving task allocation priority to the nearest agent).

Robots for future space missions could be designed to be capable of all servicing tasks, including the fine level of manipulation needed for electrical connectors and tethers. The tethers that are used on-orbit to restrain hardware from floating away if inadvertently dropped are sent up with every mission in the Shuttle. The tethers could also be redesigned for future missions to facilitate robotic manipulation. An ideally designed robot performing all required tasks would achieve the absolute minimum solution for human involvement time but does not further the study of human and robot cooperation during space activities. A purely robotic servicing mission had been designed and considered by NASA for the original SM4 [14]. That line of research was not repeated in this effort.

Having subtasks performed by a combined human and robot team introduces shared workspace and interference issues that were not addressed in this effort. The robotic agent could be specifically designed to incorporate situational knowledge to safely monitor the human crew. This could enable the robotic agent to work safely and independently within the same workspace as the human crew. This would increase the schedule benefits beyond those described in this research effort but would require incorporation of a much more sophisticated sensor and fault detection system.

6. Conclusions

This work provides a guide to develop a better estimation of the contribution of a robot to human productivity during space mission activities. Including a dexterous robot in servicing activities has the potential to greatly reduce the human crew's active involvement time in mission tasks, allowing them to work in parallel on additional tasks. This in turn will allow a larger volume of tasks to be completed than during an equivalent human-only time window.

This research facilitates the ability to more accurately predict how much the human crew's wait time could be reduced by various robotic configurations. Analysis of the effect of the RPP on the cooperative schedule provides framework for using human time window constraints to back out the required robot performance time to maintain an efficient cooperative schedule. This in turn can be used to set robot design requirements.

These results were developed using the cooperative human and robotic task allocation and scheduling methodology that had been previously developed [7]. This methodology was expanded to characterize the effect of the robotic agent's task performance on the human crew's schedule and to determine from this performance a cost–benefit of the robot's performance speed for its task set.

A method was demonstrated to influence the selection of robotic design capabilities and to determine a performance basis that the robotic agent must have to be an effective and efficient supplement to the standard two-human extravehicular activity crew for on-orbit servicing activities.

Acknowledgments

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Appendix A. Acronyms from Fig. 4

486 Comp: computer upgrade
A/L Ingress: airlock ingress
EVA: extra-vehicular activity
FGS: fine guidance sensor
HST SM: Hubble Space Telescope servicing mission
MFR: manipulator foot restraint
MLI: multi-layer insulation blanket
NOBL: new outer blanket layer
OCE-EK: optical control electronics-enhancement kit
PFR: portable foot restraint
PRT: power ratchet tool
RMS: remote manipulator system
RSU: rate sensor unit
SSAT: S-band signal access transmitter
SSR: solid state recorder
SSRF: shield shell replacement fabric
VIK: voltage instrument kit

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