THE EFFECTS OF AUTOMATION ON WORK IN SPACE

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EXECUTIVE SUMMARY

As humans spend an increasing amount of time in space, technology is driven to achieve ever greater capabilities. In fact, mankind's endeavors in space can be considered to be society's greatest technology driver. One of the most difficult challenges to be faced in the space program is that of implementing new technologies in a way that optimizes the allocation of functions between man and machine. The goal of this paper is to investigate the nature of the relationship between automation and the astronaut's work in space, particularly with respect to the following issues:

- the relationship between technology and work
- productivity versus astronaut job satisfaction
- the effect of automation on astronaut skills.

Our findings, in summary, were the following:

1. New automated technology is needed for space applications which is both mission-enabling and cost-reducing.

2. To maximize productivity, tasks should be allocated in such a way as to optimize time, economic, and human factors considerations.

3. Moderate workload levels should be ensured to avoid hypostress or hyperstress and associated problems.

4. Automated systems that enhance/augment/ extend human capabilities rather than merely replicate them should be implemented.

5. Transparency of designs and manual overrides should be incorporated to allow astronauts to intervene and troubleshoot problems.

6. Astronauts have unique experience of orbital work conditions, and their input into system designs should be solicited early to avoid costly fixes later.

7. Astronaut skill trends will tend toward less physical skills in proportion to conceptual skills, and greater skill breadth, with depth in particular critical areas.

8. The astronaut's unique ability to respond to the unforeseen will make him/her necessary to the continued exploration of space with imperfect technology.

APPROACH

The approach to this study was twofold. First, extensive literary research on the topic was performed. Secondly, original data was collected through interviews with members of several groups involved in the implementation of automation in space: NASA (management/decision-makers); contractors (executors of NASA policy/decisions); astronauts (highly trained and qualified workers in space).

HISTORICAL PERSPECTIVE

In the earliest days of the manned space program, the astronaut's role began more or less as that of a passenger or experimental subject, with most of the spacecraft's flight operations being highly automated or remotely controlled from the ground. Even then, however, the astronauts demanded to be given manual override systems to allow them to intervene and take over in case anything went wrong with a critical system. Since then, man has proven his usefulness in space time after time (see Table 1), and his role has expanded accordingly to take advantage of this. According to Nickerson, "As experience was gained and the flights became more ambitious, the crews took on more of the responsibility of piloting the spacecraft. Still later, the crew's role was expanded to include functions unrelated to piloting, such as performing scientific experiments and repairing malfunctioning equipment." The astronaut's role has evolved from that of the passenger/test subject of the Mercury program to that of the Shuttle mission manager who supervises the spacecraft's highly automated flight systems and manually performs critical space operations.

DISCUSSION OF ISSUES

Today, the technology for automating the work performed during spaceflights is just being

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developed. In fact, NASA is currently in the process of identifying requirements for the Space Station-based Flight Telerobotic Servicer (FTS), which will be the first automated maintenance/repair/assembly system to be used in space. How will the progressive implementation of such technology affect man's role in space? How will it affect productivity and the astronauts' job satisfaction? How does technology interrelate with the other forces (management, work organization, astronaut influence, skill, etc.) at work in this arena? These are the major issues around which we will focus our discussion.

The Relationship between Technology and Work

During the course of our research and interviews we have discovered that not only does technology have an effect on management decisions, skills, organization of work, and the nature of work itself, but also that management (and even the worker/astronauts) can have a profound effect on technology.

All of our interviewees agreed that NASA typically tends to push technology; that is, NASA funds the development of technology which will best enable the agency to achieve its goals. As one NASA Ames employee said, "Our job is to stay ten to fifteen years ahead of the industry." However, one astronaut we interviewed made a very keen observation of the current politico-economic situation: because of the stringent governmental budget constraints affecting current space programs, NASA will be looking more at what "off-the-shelf" technology it can adapt and use to accommodate its requirements. Another indication that economic constraints are a key influence on NASA decisions was a statement from a contractor: "A great many proposed missions could be accomplished through the application of current technology, but the costs would be unacceptable. New technology is needed which is not only mission-enabling but also cost-reducing."

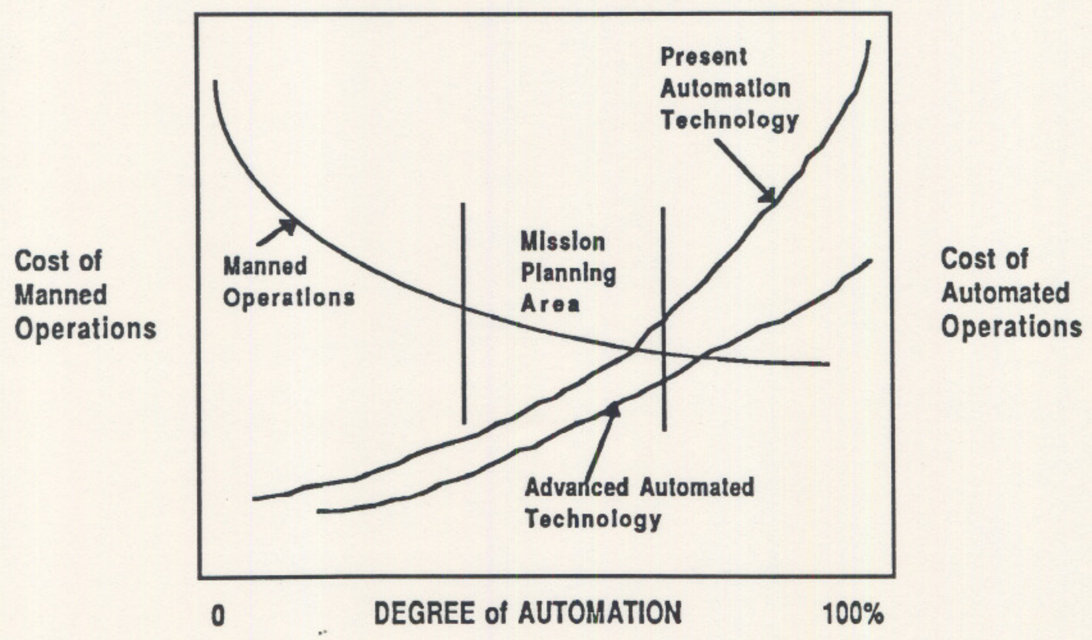

Figure 1: Cost Optimization of Automation in NASA Space Missions

Ironically, one of the most costly elements of spaceflight missions is the human. It costs approximately $25,000 per hour to keep an astronaut on-orbit, and about $35,000 per hour for extravehicular activity (EVA) time. In order to make work in space cost-effective, it is critical that astronaut time be used as efficiently and productively as possible. From a purely economic standpoint, making work in space affordable implies implementation of the least costly combination of automated versus manned operations (see Figure 1). This cost-optimized man/machine mix may not, however, be the best long-term combination from the standpoints of either productivity or astronaut job satisfaction. We will discuss this further in the next section.

Another facet of the relationship between technology and work which came up in our research and interviews is astronaut influence. In terms of power, the astronaut corps is somewhat analogous to a labor union: whereas the astronauts are not formally organized into a union with contract rights and labor union backing, they are a cohesive group and, due to their extensive training and high qualifications, they are not easily replaceable. Consequently, when it comes to implementation of technologies which could affect their work, the astronaut voice will be heard.

A case in point is the Flight Telerobotic Servicer (FTS) mentioned earlier. NASA management embarked on this project with the objective of making the FTS completely interchangeable with man, having a one-to-one correlation with human capabilities ("human anatomical equivalent" was the chosen terminology). Then recently, some astronauts who were involved in an FTS program review had this to say:

> "This is dumb. Why limit the capabilities of the robot to those of the human? Don't automate the tasks that humans are good at; automate the ones that are routine or boring or hazardous and can be done more autonomously. If I have to sit inside the spacecraft and remotely control an EV (extravehicular) robot through all its meticulous movements, I'm going to get frustrated and say, 'I can go outside and do this better myself.' The only way that type of total teleoperation will be acceptable to me is if it is for some very hazardous task."

Program	Human Action	Result
Mercury	Manual Control of Re-entry Attitude	Saved Astronaut
Apollo 10	Manual Control during Spacecraft Rendezvous and Docking	Saved Astronauts and Mission
Apollo 11	Manual Control during Lunar Landing	Ensured Safe Landing
Apollo 13	Jury-Rig of Life Support System, Rationing of Life Support Resources, Manual Control of Orbital Transfers	Saved Astronauts
Apollo 17	Lunar Rover Repair	Enhanced Mission Effectiveness
STS 41-B	Retrieval of Untethered Equipment Using Manned Maneuvering Unit	Saved Equipment
STS 41-C	Unplanned Remote Manipulator System Retrieval of Solar Maximum Mission Satellite	Saved Solar Max

Table I: Examples of Man's Ability to Respond to Unplanned Events

As a result of this input, NASA is now redefining the tasks proposed for the FTS so that it will enhance and augment human capabilities rather than replace them, and it will be a hybrid telerobotic/autonomous system rather than fully telerobotic.

Another example of astronaut influence was briefly mentioned earlier in this paper, where the astronauts in the Mercury program fought to be given manual overrides for the flight control systems so they would be able to take over if something went wrong with a critical automated system (they also fought for windows in the space capsule). This ability to override automated systems soon proved to be invaluable on John Glenn's historic flight. Glenn had to fly the capsule himself during the second and third orbits, manually reorient the capsule for retrofire, and hand fly the reentry in order to maintain the attitude necessary to avoid burning up.

The unique ability of man to respond effectively to unanticipated events has proven itself over and over again on nearly every manned spaceflight since then. Table I gives an overview of instances in which man's ability to respond to contingencies made the difference between mission success and failure. Because of these repeated demonstrations of successful human innovation in response to unplanned anomalies, NASA representatives now state that "the ability to handle contingency events is a priority capability." In this way, proven astronaut skill actually has an effect on management decisions, work organization, and technology implementation.

Productivity versus Astronaut Job Satisfaction

As we started thinking about the potential effects of automation on work in space, we began to wonder whether increased levels of automation could positively affect both productivity and astronaut job satisfaction, or if it would produce a positive effect on one and a negative effect on the other (presumably if it had negative effects on both it would not be implemented -- at least not for very long). It is the relationship between these two work attributes as they are affected by increased automation that we are interested in investigating here.

According to our sources, NASA's goal in the implementation of new technologies in space is the appropriate allocation of functions between humans and machines to maximize productivity and astronaut safety. Safety is an element of astronaut job satisfaction, which will be addressed shortly. However, "productivity" is a term suffering from lack of clear definition in the aerospace community. During the Skylab era, proving man's productivity in space was a key motivating factor for the entire program. NASA was attempting to get funding for the Space Transportation System (STS) at the time, and needed to sell Congress on the idea that humans could be productive over long periods of time at a future manned space station which would need the STS as a transportation/logistics vehicle. Today the notion that humans can be productive in space stands as an established fact, but when pressed for a definition of what that really means, most of our interviewees were rather vague. Here are some of their responses:

"Mission accomplishment."
"How much is done in a particular amount of time."
"The relationship between demands on a person and the degree of success achieved in meeting them."
"Effective and efficient use of resources in accomplishing a goal."
"Productivity is habitability."
"There is no good definition."
"It's a buzzword."

While most of our interviewees seemed to have an intuitive if perhaps abstract grasp of the term, none was able to give a widely-accepted, quantifiable definition.

NASA and several aerospace contractors have recently completed a number of studies on productivity in space. Yet because of the uniqueness of each of the Space Shuttle missions, and the as yet unknown daily activities onboard the Space Station, these studies have focussed on factors influencing productivity and how it might be maximized, realizing that absolute productivity is difficult to quantify if there is no standard against which to measure.

We finally decided that productivity is a function of how much work is done in a given amount of time for a given amount of money. Having said this, it becomes clear that the most difficult variable to quantify is "work". How does one go about measuring the work involved in running an experiment versus repairing a satellite or performing housekeeping duties or monitoring instrumentation?

Determinants of Productivity	Determinants of Job Satisfaction
Performance Capabilities	Job Match
Task Demands	Balanced Workload
Motivation	Interest/Challenge
Physiological State	Sense of Physical Well-Being
Psychological State	Sense of Security/Well-Being
Work Environment	Safety/Habitability
Organizational Structure	Control/Input/Teamwork
Man/Machine Task Allocation	Task Enjoyment
Man/Machine Interface Design	Compatibility with Tools
Resource Availability	Adequacy of Resources

Table II: Correlation Between Productivity and Job Satisfaction

Given this inherent vagueness in quantifying work and productivity, we decided to focus on the more qualitative aspects of how the implementation of automation in space will affect productivity vis a vis astronaut job satisfaction.

Most of our interviewees felt that astronaut job satisfaction and productivity were directly related, and that if automation was implemented "correctly" it would have a positive effect on both productivity and astronaut job satisfaction. Conversely, if automation was not implemented "correctly" they thought it would have a negative effect on both. This idea is supported by much of the literary research, in that it seems that many of the determinants of productivity are correlated to astronaut perceptions of job satisfaction. Table II shows a summary of these correlations.

Most of these correlations have to do with designing jobs and man/machine interfaces with human factors as a preeminent consideration. Some of the interviewees' comments relating to specific correlations are listed below:

Performance Capabilities : Job Match - "Don't automate the tasks humans are good at; automate the ones they're not good at and that machines are well-suited for: boring, repetitive, tedious, or hazardous tasks." "People are not good at monitoring-type tasks; let automated systems do monitoring for them."

Task Demands : Balanced Workload - "The workload should be neither too high nor too low... significant work overload will reduce productivity by increases in human error; significant underload will waste resources, induce boredom, inattentiveness, alienation, and feelings of underutilization and unimportance." One of the interviewees brought up the Three Mile Island incident as an example of work underload and overload: "the computer was in complete control of the system, and the operators were relaxing... the computer handed the system over to the operators as it went into alert, then fail-safe modes. The operators were not ready to make the decisions required of them - the transfer of responsibility was just too sudden. They were given too much data too rapidly to make reasonable decisions. The fault was not theirs; it was the fault of a poorly designed system." This suggests the need for a more interactive man/machine system. "We (astronauts) like this kind of work... so give us a lot to do and we'll be happy *and* productive." (Because astronauts seem to be of the mentality that thrives on challenges, their optimal workload level may be a bit higher than the average.) "Automation should be used to lessen the cognitive workload." "Teleoperators burn out in about two hours." (The mental workload for teleoperations is extremely high.)

Motivation : Interest/Challenge - "Astronauts thrive on 'pushing the envelope,' whether it's the envelope of their own physical and mental capabilities, or the envelope of technological capabilities. They like being on the edge, the frontier."

Physiological State : Sense of Physical Well-Being - "Physical fitness is important... I like the fact that my job has some physical as well as mental challenges."

Psychological State : Sense of Security/Well-Being - "Job security is important, since there is no where else to get a job as an astronaut!"

Work Environment : Safety/Habitability - "Hazardous tasks should be automated." "Productivity is habitability."

Organizational Structure : Control/Input - "We (astronauts) would like to have more input into crew activity plans and timelines." "It is important for the crew to have input into the decision-making process and prioritization of work." "Our goals are to make the astronauts feel that they are in control of the machines and that the machines are there to serve them, not the other way around."

Man/Machine Task Allocation : Task Enjoyment - "I get a lot of enjoyment out of EVA (extravehicular activity)... if I couldn't do EVA I'm not sure I'd want to fly."

Man/Machine Interface Design : Compatibility with Tools - "Incorporating more human factors considerations in man/machine interfaces will improve productivity."

Resource Availability : Adequacy of Resources - "Crew time will be a limited resource at the Space Station."

In examining the correlation between productivity and astronaut job satisfaction, one might be tempted to theorize that all that is necessary to maximize productivity is to optimize astronaut job satisfaction. However, the solution is not quite that simple. We said earlier that productivity is a function of how much work is done in a given amount of time for a given amount of money. It may be that a job which the astronaut would like to do can be done faster and/or more economically by a robot; or perhaps there is a job which the astronaut does not want to do, but given existing technology, he can do it faster and more economically than an automated system could. In these situations, tradeoffs have to be made according to how much benefit stands to be gained by having the faster, more economical system perform the task versus how much stands to be lost in terms of astronaut job satisfaction, and, all things considered, what the net effect on productivity will be.

If the goal is to maximize productivity, one must first look at whether man or machine yields a greater work output for each particular application with a fixed amount of time and money; or perhaps more appropriate for non-continuous tasks, whether man or machine is able to accomplish a given task faster and/or less expensively. Secondly, given this task-allocation based on cost and timelines, one must look at the functions allocated to the human and make sure that this role assignment provides him enough job satisfaction that it will not cause him to adversely affect productivity over the long (*or* short) term due to boredom, inattentiveness, alienation, or any other counterproductive factors. If the job satisfaction level is not high enough, it should be adjusted upward by increasing emphasis on the determinants of job satisfaction listed in Table II. Thirdly, one must look at how to optimize the human contribution through implementation of human factors in overall system design and in the design of man/machine interfaces.

Clearly, these steps comprise an iterative process in which the discovery of adverse human effects on productivity in the second step must be traded-off against the cost- and time-effective function allocation of the first step, and the final combination of human and machine functions must be integrated into a system which will optimize total productivity through careful consideration of human factors in its design.

The Effect of Automation on Astronaut Skills

The final issue we set out to address in this study is the effect on astronaut skill trends of implementing progressive levels of automation.

As mentioned earlier, the original astronauts were simply intended to be passenger/test subjects in order to study their responses and behavior in the new environments of spaceflight. For this role, NASA, at President Eisenhower's insistence, selected top fighter and test pilots who had proven their exceptional physical conditioning, motor coordination, precision of execution, spatial perception, quick response time, visual acuity, comprehension of aerodynamics, and coolness under stress, not only in their flight experience but also in the battery of tests administered by NASA during the selection process. This was the beginning of the astronauts' elite image as the very best of the best. It was also the beginning of the large differential between the skills the astronauts possessed and those actually required for the job, per se. But because of the high level of competition for the job, NASA has always been able to be very selective. And this may actually be a good thing. As manned spaceflight experience has shown us, there have been many instances in which unanticipated events have given astronauts the opportunity to use skills far above and beyond those required for the job as it was originally perceived (see Table I). Had the astronauts been any less skilled, our track record may not look nearly as impressive.

As time went on and astronauts continued to prove their capability to perform on-orbit, the job's skill requirements increased first to include performance of spacecraft piloting (attitude control, landing, rendezvous and docking) maneuvers; then scientific observations and experimentation; inspection, maintenance and repair activities; and most recently, materials processing and new technology testing. Likewise, NASA's selection criteria (and therefore the skills actually possessed by those selected) have evolved to reflect greater emphasis on breadth of skills and scientific/technical/conceptual skills, and less emphasis on physical skill (although all astronauts must still pass NASA's spaceflight physical examination). Listed below are the selection criteria for current STS astronauts, in order of importance, separated by position into categories for "Pilot", "Mission Specialist", and "Both".

<u>Pilot</u>

- Demonstrated Performance
  - Flying Experience
    >quantity and quality
    >variety
    >test pilot school
    >recency of training

- Potential
  - Trainability
  - Ability to Learn

- Stressful Environment Experience

- Responsibility

- Breadth and Quality of Experience

- Relatedness of Education and Training
  - Advanced Degree
  - Applicability and Quality

<u>Mission Specialist</u>

- Breadth and Applicability of Education
  - Advanced Degree
  - Applicability and Quality
  - Diversity
  - Recency of Training

- Breadth and Applicability of Experience
  - Quantity
  - Quality and Diversity

- Demonstrated Performance

- Responsibility and Potential

- Unique Qualifications, Skills or Experience

<u>Both</u>

- Ability to Function as a Team Member

- Communicative Ability

- Adaptability

- Motivation

If the implementation of automation in space is done in a logical manner with the goal of maximizing productivity, taking advantage of the strengths of both humans and machines, the first tasks to be automated should be those that are routine, boring, tedious, repetitive, and/or hazardous. Machines are much better suited than are humans to these types of tasks, and inexpensive technology will be available to perform these tasks much sooner than for more complex, challenging tasks. This will free up the astronauts to perform the more challenging tasks which they enjoy, as well as the duties of system management and supervision, decision-making, and trouble-shooting, for which they are much better equipped than are machines. The skill requirements for these tasks are probably not much different from those of current STS astronauts: high degree of skill breadth, scientific/technical/conceptual skills, responsibility, motivation, adaptability, teamwork and communication skills.

As we move into the Space Station era, the need for astronaut skill breadth will increase even more due to the limited availability of human resources (six on-board astronauts on three-to-six-month duty cycles will have to perform a very wide variety of tasks not only for routine Station operations and experiments, but also for unplanned maintenance and repair contingencies on the Station and other earth-orbiting spacecraft). Piloting skills will be used less frequently at the Station; only once every three-to-six months for the Earth-to-Station roundtrip, and any emergency earth-returns between times. Piloting will remain a critical skill, but the pilot will have to become more of a generalist as well, with depth in that one area.

As technology advances and automation becomes the more efficient and productive method of performing more and more of the astronauts' manual tasks, most of our interviewees believed that along with a continuing need for a broad skill base, the balance of astronaut skill requirements would shift progressively away from physical skills in proportion to conceptual skills. As this trend in job requirements becomes more clear, NASA should probably modify its selection criteria accordingly, as many of the current astronauts expressed experiencing a great deal of satisfaction in the "hands-on" aspects of their jobs.

In general, it would seem that astronaut job requirements over the long term would tend toward increasing skill breadth, less physical skills in proportion to conceptual skills, and more individuals who are generalists with depth in potentially critical areas (such as piloting, medicine, EVA, automated systems and robot repair).

RECOMMENDATIONS and CONCLUSIONS

To summarize the primary conclusions and recommendations of this study:

- New technology is needed for future space projects which is both mission-enabling and cost-reducing.

- Since the goal is to maximize productivity and astronaut safety, tasks should be allocated to man and machine with the objective of optimizing time, economic, and human factors considerations.

- Ensuring a moderate workload is critical to avoiding astronaut hyperstress and hypostress and the associated problems of human error and alienation, although the optimal workload for astronautss may be higher than average due to their unique personality characteristics.

- In order to optimize the man/machine mix, the philosophy of incorporating systems for experts rather than expert systems should be followed. This will enhance, augment, and extend the human capability rather than merely replicate it, and it is more cost-effective to implement complementary rather than redundant systems.

- Transparency of design is an important feature in allowing the astronaut to do what he does best: that is, troubleshoot problems. Transparent design of systems and hardware enables the user to understand how they operate, and to have a logical idea of where to begin looking for potential problems.

- Provision of manual overrides in the design of automated systems and hardware is necessary to enable astronauts to intervene and take over operations in case problems arise.

- Astronauts have unique experience of zero gravity and pressure-suited working conditions, and their input should be solicited and heeded early in the design and development of automated systems in order to avoid costly fixes later.

- Astronaut skill trends will tend toward less physical skills in proportion to conceptual skills; greater skill breadth (i.e., generalists) with depth in individual critical non-automated and/or override functions.

- Selection criteria and training programs should be modified to reflect the skill changes as they become more evident, so that astronauts continue to have realistic expectations about their jobs, and are well-suited to them in terms of skills possessed versus skills required.

- Finally, man's unique ability to respond to the unforeseen will make him crucial to the continued exploration of space with imperfect technology.

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