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# Telesupervised Co-Robotic Systems for Remote Confined/Hazardous Space Operations

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*Abstract* – **By deploying human workers remotely using telerobotic technologies into confined or otherwise hazardous spaces, the human workers' skills are brought to tasks but not to the dangers. This translates into elimination of musculoskeletal injuries; removal from exposure to harmful atmospheres; and reduced cognitive load. These characteristics result in higher productivity and quality; and allow experienced workers to continue to exercise their skills over a longer period and retain healthier outcomes.**

## I. Introduction

The assembly of major aircraft components involves ergonomically-challenging tasks in confined spaces. Tasks include: gauging, fastening, sealing, cleaning, coating, and inspection – inside of the wings/fuel tanks, and fuselage. Boeing is addressing these tasks with co-robot technologies – human capabilities augmented by robotic technologies – substantial increases in productivity and worker safety may be realized.

A Co-Robotic Telesupervision Architecture is presented that supports human-robot teams to safely leverage each other's' strengths. Enhancing human senses with high-fidelity telepresence, improves situation awareness. Extending human cognition with autonomous intelligent agents augments human reasoning and reduces cognitive load.

In the following sections we describe our co-robotics telesupervision architecture, high-fidelity immersive telepresence, co-robotic telesupervision workstation, and intelligent assisting agents. We also describe an experimental system to be built on these principles for remote operation inside the confines of a wing bay, and the formal testing methods to be used to validate this system.

## II. Co-Robotics Telesupervision Architecture

Of the many forms that humans working with robots may take, we focus on a systemic approach to augment human capabilities. This includes extending human senses and reach physically; modifying human senses in scale both geometrically and spectrally; and expanding human cognition.

Recognizing the limits of autonomy that preclude direct leaps from the majority of human-accomplished tasks to fully-automated tasks, we take a tractable approach to selectively integrate augmentation of human sensory and cognitive capabilities. Within our open architecture of human/autonomous cooperation, we support multiple layers: from direct human teleoperation; to augmented human operations; to high-level human supervision of autonomous actions. The open telesupervision architecture, developed by the first author, has supported research for planetary exploration using semi-autonomous rovers for NASA's Exploration Systems Mission Directorate; and research for Harmful Algal Bloom detection by semi-autonomous ocean vessels for NASA's Earth Science Technology Office [Podnar et al, 2008]. The architecture provides a framework within which co-robotic assembly and inspection systems can be continuously improved as intelligent autonomous agents are developed, proven robust, and integrated.

The primary elements of our co-robotic telesupervision architecture (Figure 1), instantiated as a system for remote confined space operation are: the distal robotic sensory and manipulation tools; the proximal immersive telepresence and manipulation controls of the telesupervisor's workstation; and the interposed intelligent assisting agents.

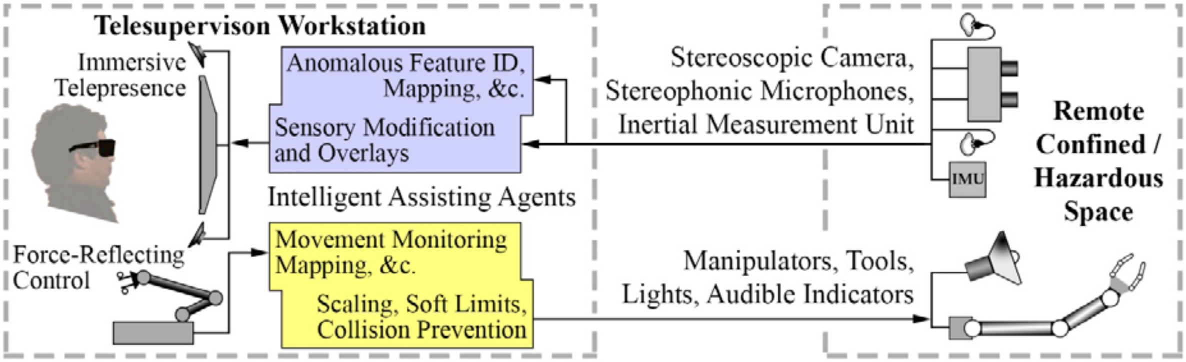


*Figure 1. Co-Robotic Telesupervision Architecture with autonomous agents for human augmentation.*

*A. Distal Robotic Systems*

Sensory and manipulation systems are deployed into confined/hazardous spaces such as fuel tank wing bays. These include: teleperception sensors for binocular stereoscopic vision, binaural stereophonic audition, proprioception, and force-reflecting haptic manipulators. These are deployed using robotic vehicles or arms adapted to the tasks, spaces, and access. For example, access through a relatively small convoluted passage may require a snake-like robot vehicle.

*B. High-Fidelity Immersive Telepresence*

Situation awareness and the sense of presence requires high-fidelity acquisition and presentation of sensory and sensorimotor data. Telepresence presentation to the telesupervisor includes geometrically-correct binocular stereoscopic viewing systems [Grinberg, Podnar, Siegel, 1994 and 1995] and high-fidelity stereophonic audio reproduction. Force-reflecting manipulation allows the teleoperator to feel into the environment. The attitude (orientation) and vibration of the co-robotic vehicle or end-effector is relayed to the telesupervisor’s chair for Vestibular Spatial Orientation and 'seat-of-the-pants' proprioception.

*C. Co-Robotic Telesupervision Workstation*

By integrating high-fidelity operator interface components for mobility, manipulation, and telesensing, the Co-Robotic Telesupervision Workstation becomes the hub of planning and control. The telesupervision workstation is situated in a human-safe environment. Direct human teleoperation is augmented by intelligent assisting agents.

*D. Intelligent Assisting Agents*

The immersive telepresence and teleoperation data are communicated between the distal robotic systems and the Telesupervision Workstation and thus are available to the Intelligent Assisting Agents that can autonomously monitor, interpret, indicate, automate, and limit. Some high-level robotic autonomy is relatively mature, such as robot path planning and navigation. Others such as automatic task-specific operations, and system 'health' monitoring are less robust or must be developed per application. Figure 1 identifies some Agents, not detailed here due to the page limit.

The architecture supports development of autonomous agents as each co-robotic system task domain is analyzed and defined allowing their modular development, testing, and incorporation. Graceful fall-forward/fall-back between autonomous agents and direct teleoperation is one of the key strengths of our modular augmented telesupervision.

*E. Distant Human Expert Telecollaboration*

A further expansion of the concept of the "intelligent assisting agent" that is supported by our architecture is the facility to provide a subset of the telepresence data to a distant *human* expert who has more specific domain knowledge than the telesupervisor operating through the co-robotic system. This is especially useful when an unforeseen condition is experienced for which additional expertise is required. By supporting this telecollaborative access to a wide variety of distant domain experts, unexpected situations can be addressed rapidly, without the time and cost to co-locate the experts for consultation.

## III. Experimental Testing of a Co-Robotic System for Operating Inside the Confines of a Wing Bay

Our design principles for a co-robotic system for internal wing bay assembly and inspection tasks, and our testing methodology are predicated on fundamental requirements: the deployed robotic equipment must be physically capable of accomplishing the domain-specific tasks; the deployed sensing capability must provide situation awareness with sufficient fidelity to remotely accomplish the goal tasks; and the workstation must provide the most natural interfaces practical using Human Factors and Ergonomics design principles.

*A. Comprehensive Testing and Validation*

Performance experiments of the co-robotic system for wing bay assembly and inspection tasks, will prove the effectiveness of integrated telepresence, teleoperation, and human augmentation technologies. This formal approach is appropriate to validate every task-specific co-robotic system developed within our telesupervision architecture.

Participants will be volunteers who are familiar with the airplane wingtip final assembly close out inspection and fastener installation tasks. (Experimental protocol, human subject recruitment and selection, and methods collection and storage must be approved by the Boeing Human Subjects Review Board before any human subject recruitment and testing takes place.)

To achieve statistical power of .8 or greater, we will seek to recruit a minimum of 7-10 participants for each set of experiments, and to encompass the range of age, experience, and physical characteristics for the 5th, 50th, and 95th percentile of the population. Subjects may be screened for prior musculoskeletal injuries, and anthropometric measurements.

### *B. Experimental Design*

We will utilize a within-subjects, repeated measures design, with participants completing the experimental tasks in all conditions. Independent variables will include task (inspection and fastener installation) and work method (manual operation and remote co-robotic system operation). Order effects will be counter-balanced.

Human subjects will separately (in counter-balanced order) perform two different types of wing bay close out tasks, inspection and fastener installation, both manually, and remotely through the co-robotic teleoperation system. The tasks will be conducted in full-scale, analogous mockups of aircraft wingtip build section wing bays chosen because they offer very limited physical and visual access to the points of operation thus making them an excellent candidate for co-robotics technology improvements.

Recognizing that while workers are remoted from the confined space environment, they will be working through an interface that may itself pose ergonomic issues. Therefore the co-robotic telesupervision workstation developed for this testing will first be assessed using a musculoskeletal disorder risk factor checklist. Interface devices and features of the co-robotic workstation include:

- Immersive human interfaces to remote sensory systems.
- Intuitive human controls for telerobotic actuation.
- Geometrically-correct binocular remote vision system.
- Binaural stereophonic remote audition system.
- Autonomous vision agent to detect ‘features-of-interest.’
- 3D visual overlay with mode selections.
- Height-adjustable, positionable chair or sit/stand stool.

### *C. Tasks and Procedure*

Wing bay interiors are extremely difficult to access, often requiring mechanics to work by touch only and in cramped spaces. Subjects will perform two different wing bay final assembly close out tasks: fastening and inspection; both manually (as currently done today), and telerobotically (using the co-robotic telesupervision system). These will be conducted in three wing bay mockups with limited levels of access: one arm only with no visual access (blind reach); head and one arm; head and both arms.

Fastener Installation Task: Subjects will perform analogous fastener completion tasks using a tool to install collars or nuts on fasteners pre-inserted from the exterior.

Inspection: Subjects will perform final assembly close out inspection tasks for irregularities, proper installation of fasteners, and for foreign object debris.

### *D. Evaluation Methods*

We will utilize measures of task performance, usability testing, and workload assessment. Objective measures include task completion times, frequency/type of errors, and quality acceptance ratios (e.g., in an inspection task, how many incomplete fasteners were correctly identified). Usability evaluations using formal testing methods [Barnum, 2002], will take advantage of our research in usability testing with teleoperated robots supported by NSF (IIS-0636173) and Army Research Laboratory (ARO 103526, W911NF-06-2-0041). We use a set of measures that are especially suited to remote robot operations that provide indirect indication of the quality of interface design including task completion time, the number of objectives accomplished within a time, and subjective surveys [Burke et al, 2008].

We will measure workload using the NASA TLX (Task Load Index) method [Hart and Staveland, 1988]. Users provide subjective assessments along scales in six dimensions: mental demands (how much thinking, looking, calculating, remembering, searching), physical demands (how much pushing, pulling, turning, activating), temporal demands (how much time pressure), performance (how well did the user think they performed the task), effort (how hard did the user have to work), and frustration (how irritated, discouraged, stressed or annoyed was the user) This technique is well-suited to a within-subjects experimental design so that individual differences in perceiving workload affect all conditions equally.

### *E. Situation Awareness (SA)*

Situation Awareness is a critical component of robot teleoperations [Endsley, 1988]. We will evaluate the interface conditions in terms of their contribution to enhanced operator SA using coding schemes modified from previous research [Burke et al, 2004] wherein operators spent much of their time trying to determine the state of the robot (its location, configuration, mode) [Burke & Murphy, 2007]. The investigators code operator "think aloud" utterances according to pre-determined categories, e.g. content, task, robot state, etc. Of interest are the hypothesized benefits of multi-modal feedback to the operator: visual augmentation, force-feedback, and scaled operation [Burke et al, 2006].

*F. Musculoskeletal Disorder (MSD) Risk Assessments*

We will perform MSD risk factor assessments while operators perform tasks manually and while using the co-robotic system. Measurement devices and equipment include:

- Standardized checklists and surveys to assess MSD exposure.
- Physiological measurements (e.g., respiration, heart rate).
- Photography and video.
- Force/pressure mapping,
- Motion capture and goniometers for measuring posture.

These MSD risk data provide quantitative information to help determine if there are differences between manual and co-robotic system risk.

*G. Data Analysis*

Parametric statistical procedures such a balanced multifactor repeated measures analysis of variance (ANOVA) will be used to analyze ratio-scale data collected, e.g., task performance times. Nonparametric statistical procedures will be administered to ordinal and interval-scale data, such as numerical questionnaire data. Simple descriptive analyses will also be completed on each study group separately. Variables of interest include typical demographic characteristics.

*H. Outcomes, tied to research questions*

The results gathered from this research will increase knowledge of task performance outcomes with new teleoperation techniques and technologies; identify the types of feedback most effective in assisting operators; and understand the ergonomic improvement associated with new ways of performing confined space manufacturing operations.

## V. Conclusion

Removing workers from confined and hazardous spaces eliminates risk, reducing the probability of injuries. Augmenting the humans' capabilities with intelligent assisting agents reduces cognitive load for improved productivity and quality. Experienced workers can exercise their skills over a longer, healthier career. Use of the co-robotic system will also eliminate personal protective equipment, training, certification, and oversight.

The ability to "scale" the worker through co-robotic systems allows the expansion of the design space, supporting design of significantly higher-performance systems that would be unable to be assembled by conventional means.

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