MATCHING FEEDBACK WITH OPERATOR INTENT FOR EFFECTIVE HUMAN-MACHINE INTERFACES

Ph.D. Thesis Proposal

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ABSTRACT

Various roles for operators in human-machine systems have been proposed. The proposed research hypothesizes that underlying all of these views is the law that operators perform best when given feedback of the same type as their intent. To test the hypothesis, operator performance with position control, rate control, and position control with the ghost arm will be measured to see if giving position feedback will demonstrate its advantage over rate control and explain the previously found advantage of rate control. Past studies have shown that position control is superior to rate control except when operating large-workspace and/or low-bandwidth manipulators and for tracking tasks. Operators of large-workspace and/or low-bandwidth manipulators do not receive immediate position feedback. To remedy this, a ghost arm overlay will be displayed for them. Operators will also perform different tasks (point-to-point motion, tracking, path following, etc.) with different controllers (position control, velocity control) under different task conditions (obstacles, bandwidth of the machine, etc.) to measure how different task factors influence the operator's intent. The feasibility of using a ghost arm for teleoperation will be investigated by displaying the arm with 3DTV technology. Unlike previous work, this research will compare the fuel efficiencies of different HMIs as well as time efficiencies.

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1. INTRODUCTION

Operator performance depends heavily on feedback from the system being controlled. Many types of human-machine interfaces (HMIs) have been invented to provide the operators with feedback to better their performance along some metric. The proposed research hypothesizes that effective HMIs must give the operators feedback of the same type as their intent, or, in other words, of the same type as how the operators view their goal (see Fig. 1).

Birmingham proposed that people perform best when their transfer function is as simple as possible. He viewed the goal of HMIs to be the simplification of the operator's transfer function to a simple amplifier [Birmingham]. As automation technology improved, Fitts proposed list of what men and machines do best [Fitts]. Fitts' list were generally used to assign tasks to either the operator or the machine [Wickens, Corliss]. Sheridan suggested keeping Fitts' list, but instead of assigning each task to either operator or machine, to assign the task a level of control from both operator and machine, an idea contrary to Birmingham's hypothesis that a human "is best when doing least" [Sheridan (2000), Jordan, Birmingham]. He called this strategy supervisory control [Sheridan (1978)]. Sheridan outlines the operator's role as being much more complex than a simple amplifier in a supervisory control system; the operator is a planner, monitor, and teacher [Sheridan (1989)].

This research proposes a theory that underlies both views: Effective HMIs must give the operator feedback of the same type as the operator's intent. In Birmingham's case, the operators controlled either the position or velocity of a single degree-of-freedom. The operators likely viewed their intent as a position or a velocity, although the they were not asked and no attempt was otherwise made to determine how they viewed their intent. In Sheridan's case, the operator's goal is not necessarily a given position or velocity, but rather a "goal state" [Sheridan (1992)]. The "goal state" can be accomplishing a task, e.g., picking up an object. Although Sheridan's and Birmingham's methods of helping operators accomplish a task differ, both attempt to provide feedback to the operator of the same type as the operator's intent.

To investigate whether having feedback of the same type as the operator's intent improves performance, HMIs for large-workspace, low-bandwidth manipulators will be designed. Most HMI research has focused on human-scale or smaller manipulators with human-scale or faster bandwidths [Mora, Jenkins]. For these systems, position control has been shown to outperform rate control [Kim, Zhai (1993a)]. This has led to position control being accepted as generally superior to rate control and fostered the idea that position control is more intuitive [Sheridan (1978)]. However, for large-workspace and/or low-bandwidth manipulators, rate control performance exceeds position control performance [Kim, Zhai (1997)]. Because of the large workspace and low bandwidth, operators of these manipulators do not receive the immediate visual position feedback that operators of smaller and faster manipulators do. They do receive immediate visual rate feedback.

The proposed research will investigate if a new HMI that couples position feedback with position control for large-workspace, low-bandwidth manipulators will establish an advantage for position control for these manipulators and explain the previously found better performance with rate control. To do this, a graphical overlay of the input position will be displayed to the operator. Operator fuel and time efficiency will be measured to determine the effectiveness of the new HMI, unlike previous studies that have only examined time efficiency. The feasibility of using 3DTV technology to display the overlay for teleoperation will be investigated. The types of mistakes operators make with different HMIs will be quantified and examined for possible changes to the HMI that would lessen or remove the mistakes.

The proposed work will also investigate if certain task conditions influence the operator's intent. For example, despite the general advantage of position control, rate control outperforms position control for tracking tasks [Zhai (1993b), Zhai (1997)]. A series of human factors tests with different tasks (e.g. tracking, point-to-point motion) and different task conditions (e.g. the presence of obstacles, the bandwidth of the manipulator) will be performed with both position and rate control to determine if the task conditions affect the operator's intent.

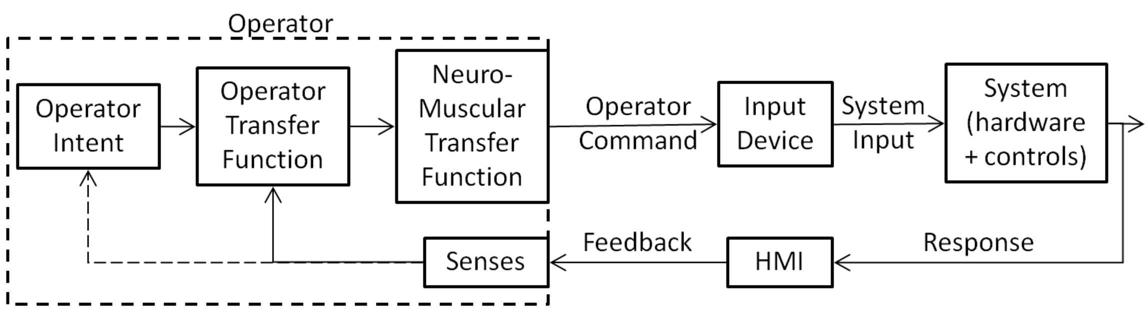

Figure 1. Signal notation for operator control loop.

2. BACKGROUND

2.1 Operator's Role in Human-Machine Systems

As early as the 1940s, attempts were made to determine the human transfer function [James, Tustin]. They found that there is not a single human transfer function, but many, and that humans adapt their transfer function to maximize performance. Birmingham theorized that men are better or worse at different transfer functions, so controls engineers should design in a way to minimize the complexity of the operator's transfer function because humans are better at simple transfer functions [Birmingham]. He viewed the best case scenario to be that the operator's transfer function is only an amplifier. He proposed two methods to accomplish this, quickening and aiding, and showed that they improved operator performance (see Section 2.2.1 for descriptions of quickening and aiding). He was interested in controlling systems that had a single position or velocity output.

As the fields of human factors engineering and engineering psychology emerged, the scope of what the "system" was in a human-machine system widened [Chapanis]. It moved from single degree-of-freedom systems like Birmingham studied, to complex computer and mechanical systems, such as nuclear reactors and airplane cockpits. Instead of studying operators that had a given position or rate as a goal, the field focused on operators with more complex goals composed of many tasks, such as safely producing electricity with a nuclear reactor or landing a plane. The output of the system was no longer directly dependent on the human's input because some processes were partially or fully automated.

Fitts proposed a list of what men and machines do best (see Table 1). Control was given to either the operator or the machine. The operator's role was either completely eliminated (the process was entirely automated) or the operator controlled the job completely. Better automation became the solution to better performance, again trying to keep the operator's role at a minimum.

Men Are Better At	Machines Are Better At
• Detecting small amounts of visual, auditory or chemical energy • Perceiving patterns of light or sound • Improvising and using flexible procedures • Storing information for long periods of time, and recalling appropriate parts • Reasoning inductively • Exercising judgment	• Responding quickly to control signals • Applying great force smoothly and precisely • Storing information briefly and erasing it completely • Reasoning deductively

Table 1. Fitts' List

Sheridan and Verplank proposed levels of automation based on the ratio of human control to computer control [Sheridan (1978)]. They proposed ten levels and called their theory supervisory control. The underlying idea was not to minimize the operator's role, but to maximize performance by using the strengths of both operator and machine simultaneously. More recent research has extended this view from assigning static levels to the control ratio to changing the control ratio based on the situation [Parasuraman].

2.2 Interfaces that Provide Feedback Matching the Operator's Intent

Many HMIs have been developed that improve operator performance for mechanical systems. None of the researchers that invented these HMIs stated that matching the operator's intent with the feedback from the machine was a goal. However, it is explained in each subsection how they inadvertently accomplished this goal.

2.2.1 Aiding and Quickening

Birmingham proposed both aiding and quickening to simplify the operator’s transfer function [Birmingham]. An aiding control block is the inverse of the dynamics of the input device. This block is inserted directly after the input device to negate the filtering of the operator’s command by the input device (see Fig. 2). This simplifies the operator’s transfer function because the operator does not have to act as the inverse block. The system feedback better matches the operator’s intent because the operator’s intent does not take the input device’s dynamics into consideration.

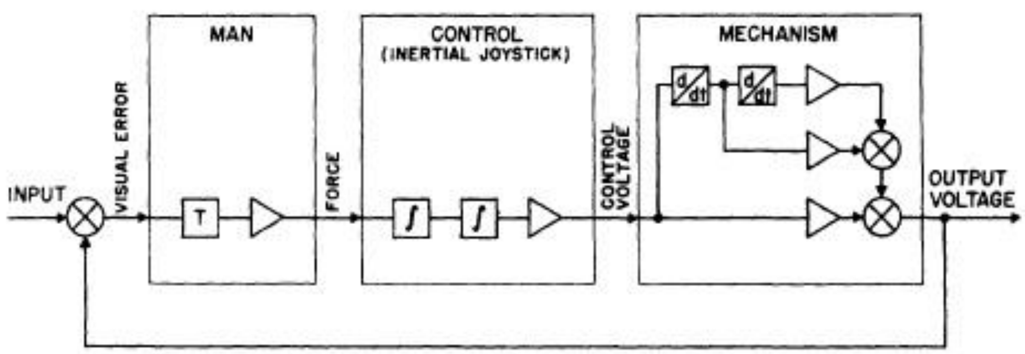

Fig. 6—Tracking system with an inertial joystick and perfect aiding.

Figure 2. Aiding control from [Birmingham]. The aiding is in the “mechanism” block.

Quickening is used for systems with very slow dynamics. A quickened system shows the future state of the machine based on current input. It provides anticipatory visual feedback based on the derivatives of the states. In many ways, this is similar to PID control, but it is applied to the feedback rather than the system input (see Fig. 3). This is useful when the operator’s command effects the acceleration or jerk of the machine, but he/she is interested in position. For example, submarines have used quickening displays because of the slow response of the position of the submarine to the angle of the depth-controlling surfaces [Johnsen, Corliss]. This better matches the operator’s intent and the system feedback because it provides visual feedback of the same derivative order as the operator’s intent.

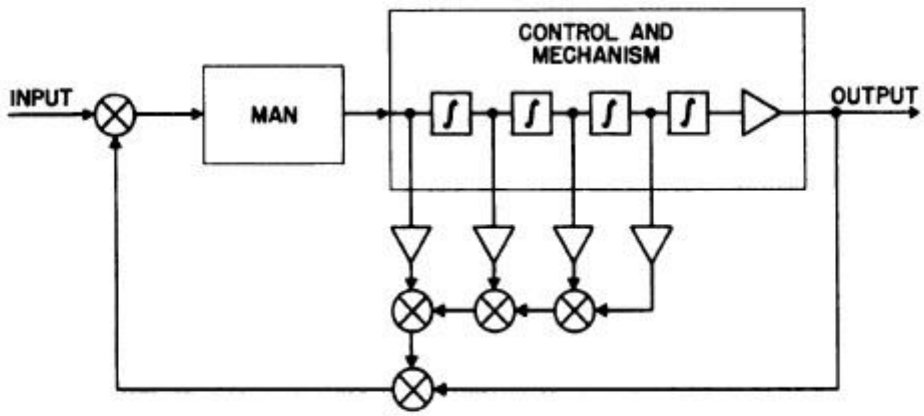

Fig. 10—The control system with quickening taking effect on display.

Figure 3. Quickening display from [Birmingham].

Both of Birmingham’s methods assume that the operator’s intent and the feedback are of the same type. This allows a direct comparison between them.

2.2.2 Supervisory Control

Supervisory control “zooms out” a level and views the operator’s intent as a larger overall goal rather than one specific state of the machine. The challenge of supervisory control is giving the correct feedback to the operator to accomplish the goal. Much research has gone into the types of controls, displays, and environment to best help the operator [Wickens, Sanders]. How to integrate the automatic and human-controlled processes continues to be an active area of research [Bunte, Lin].

Since the proposed work will focus on hydraulic machinery, it should be mentioned that some work has focused on automating tasks such as excavation [Stentz].

While perhaps full automation of excavators will not be soon in coming, some excavators sold today come equipped with auto-dump and auto-return capabilities.

2.2.3 Coordinated Control Research

Coordinated control better matches the operator's mental model of the tasks to be done [Wickens]. In other words, the operator controls the end effector's position or velocity in a way that matches the way he/she views the position or velocity as occurring, i.e., in terms of left-right or up-down positions/velocities instead of a sets of joint positions/velocities. Controlling the joint positions/velocities directly requires the operator to mentally solve the inverse kinematics of the manipulator. Coordinated control relieves the operator of this cognitive load. Coordinated rate control has been shown to enable novice operators to more readily control hydraulic equipment [Lawrence, N. Parker, Wallersteiner]. Coordinated position control has been shown to be more effective than coordinated rate control in most circumstances, especially for novices [Kim, Zhai (1997)].

[Kontz] implemented coordinated position control on a backhoe, but found that the magnitude of the cab vibrations was great enough to lead to instability due to the biodynamic feedthrough. NASA also suggests rate control in the presence of vibrations for the same reason [J. Parker].

Even in the absence of vibrations, coordinated rate control has been shown to outperform coordinated position control for large-workspace and/or low bandwidth manipulators. When using position control for manipulators with slower dynamics, there is not a clear indication to the operator where the position he/she is commanding is located because the manipulator takes too long to arrive at the input position. This causes a "move and wait" tactic [Sheridan (1989)].

2.2.4 Predictive Displays

Predictive displays show the operator the predicted state of the machine given the current input and computer-estimated future inputs. A simple example of a predictive display would be one that assumes the operator's rate command will remain constant and displays the manipulators position at some time interval in advance. These are used in very fast systems (e.g. jet planes) to extend the operators' knowledge of how their command will affect motion in the near future [Johnsen, Kelley]. In this case, the predictive display shows the operator's future path because the operator must make input adjustments now because he/she is unable to correct fast enough in real-time in the future (e.g. he/she must command the jet to gain altitude before approaching the mountain, not because the jet cannot perform appropriately, but because the operator react and correct quickly enough).

Predictive displays have also been shown to be effective in communication time delay situations [Sheridan (1992)]. The operators are shown what the effects of their input are from a faster-than-real-time model. He/She no longer has to wait to see how the machine responds, if the model is accurate. Predictive displays effectively remove the time delay from the operator's transfer function. Other HMIs have been proposed for teleoperation with time delay, most of which attempt to accomplish greater usability and/or productivity by removing the time delay from the operator's transfer function [Niemeyer]. Providing non-delayed feedback better matches the operator's intent because he/she views the states of the machine in real-time.

2.2.5 Ghost Arm Compensation for Communication Time Delay

Teleoperation comes with time delays in the communication channel between the master and the slave. To overcome the effects of time delay, [Noyes] built a two dimensional wire frame “ghost arm” overlay of the robot arm being controlled and superimposed it on the delayed video feed of the robot arm. The wireframe overlay showed the telemanipulator’s model-based predicted location at the current time. This allows the operator to control the wireframe arm without any communication delay. As noted by Noyes, this technique is only as good as the model, and it is difficult to model environmental interactions. Noyes used an Argonne E-2 manipulator that has fast dynamics, so the position of the overlaid ghost arm on the screen was basically the same as the operator’s position command. [Conway] furthered this idea by constructing a teleoperation system with a ghost arm that had a time and position clutch. The time clutch allowed the operator to quickly move the ghost arm to define the path that manipulator end effector should follow, without being constrained by the dynamics of the telemanipulator. Disengaging the position clutch disconnected the controller from the input stream. With the position clutch disengaged, the operator could move the ghost arm freely about, taking time to position it for the beginning of a complicated maneuver. Once the operator has it in the correct location, he/she re-engages the position clutch, and that position is entered into the input stream. The goal was to save time with the time clutch on fast, easy maneuvers and then to use the saved time on positioning for complex maneuvers, all while mitigating the effects of time delay in the same fashion as Noyes. Both Noyes and Conway showed improvements in task completion times with their HMIs.

2.3 Previous Work Completed

2.3.1 Excavator Simulator Testbed

To test the efficiency of different human machine interfaces, each interface needs to be used on the same machine to do the same task. Implementing the interface and necessary sensors on a hydraulic manipulator is expensive and time consuming. To more quickly test, ensure operator safety, and maintain task repeatability, an excavator simulator was constructed [Elton (2009)]. A hydraulic excavator was selected as the testbed for this study because excavators are common large workspace, low bandwidth manipulators.

The simulator mimics the dynamics of the excavator's hydraulic and mechanical systems and the interaction with the environment. The simulated arm and environment are displayed to the operator on a 52 inch LCD TV that is mounted to the windshield of a Bobcat 435 excavator cab. The operator sits in the cab to manipulate the input devices, while sound proportional to the engine load is played. Two input devices have been installed in the cab, electronic joysticks like those used in similar equipment, and a Phantom Premium 1.0A. The Phantom is used for coordinated control.

2.3.2 HMI Research Previously Performed on the Excavator Simulator

Human subject tests that measured operator performance for different HMIs have already been performed using the simulator. The first study investigated the effects of different types of one-handed coordinated control and haptic feedback on operators' trenching performance [Elton (2011a)]. Operators performed better and preferred coordinated Cartesian position control to coordinated cylindrical "hybrid" (mixed position and velocity) control despite being in a rotating reference frame that was similar to the cylindrical coordinate frame. Performance was also better without force reflection.

The second test compared the best performing HMI for the first test (Cartesian coordinated control without force reflection) to the standard non-coordinated joystick HMI. Novice operators increased productivity by 86% in terms of soil removed from the trench per unit time. They used 57% more energy/time, for an overall 19% increase in task efficiency (soil removed/energy consumed) [Elton (2011b)].

2.4 Human-Machine Interfaces for Hydraulic Manipulators

2.4.1 Evolution of Human-Machine Interfaces for Hydraulic Manipulators

Human-machine interfaces for heavy hydraulic manipulators continue to evolve. These manipulators were first controlled directly by levers or pedals that directly moved the valves controlling the manipulator. Then, pilot-operated valves were implemented that allowed the operator to control a smaller valve requiring less force to move that would in turn move the valves controlling the manipulator. These have been replaced in part by electro-hydraulic systems. In these systems, the operator controls the valves by moving electronic joysticks or other input devices that send a current to a solenoid that moves the valve spool. Since the operator's controller and the manipulator are only electronically connected, new possibilities emerge such as teleoperation [Andreychek], coordinated control [Wallersteiner], and artificial force feedback (as opposed to the forces fed back from the mechanical or hydraulic coupling) [N. Parker, Kontz, Zhu].

2.4.2 Why Move Towards Teleoperation?

There are several benefits to removing the operator from the machine, including safety. Worksites for hydraulic machinery are often hazardous. Specially designed excavators are used for the handling of nuclear waste and are teleoperated to protect the operator from radiation exposure [Andreychek]. The construction of ports requires expert divers to drive specialized excavators underwater [Hirabayashi]. When forest harvesting, trees can, and occasionally do, fall on machine operators – these trees are known in the business as widowmakers. Underground mines have the potential to collapse, such as the recent Upper Big Branch Mine collapse in West Virginia (5 Apr 2010, 29 dead), the Copiapó collapse in Chile (5 Aug 2010, 33 miners trapped for 69 days), and the Pike River collapse in New Zealand (19 Nov 2010, 29 dead). Even at everyday construction sites, accidents happen regularly. Removing the operator from the machine would increase operator safety.

There are other benefits to removing the operator from the machine. The operator could move to a different location to better view the end effector during precision tasks. Vibratory feedthrough would be eliminated if the operator no longer sat on the machine. Teleoperation would also allow the operator to work remotely. This would let the operator switch between worksites quickly rather than commuting between them. Time that previously would have been spent sitting idle at a job site waiting until other tasks were completed could instead be used doing work at another site. Operators would no longer have to live at remote locations, such as the Challenger mine in the Australian Outback that operates on a fly-in fly-out roster.

Placing the operator at a remote location would remove all of the feedback to the operator. It would need to be replaced by sensors and an HMI. Teleoperation increases the freedom in designing HMIs. While sensors and interface devices could be costly, this cost would be offset because machines would no longer need a cab to house the operator, which often includes climate control, plush seats, and other expenses in addition to the cost of the materials and manufacturing the of the cab's metal, glass, etc. [Herrin].

3. WORK TO BE PERFORMED

The proposed work seeks to verify if feedback of the same type as the operator's intent increases operator performance. Past research has shown that performance with position control exceeds that of rate control except for tracking tasks and for controlling large workspace and/or low bandwidth manipulators. Hypothesized is that position control would be more efficient for large workspace and/or low bandwidth manipulators if the operators were given feedback indicating what the input position was. A comparison of the different HMIs (position control, rate control, position control with ghost arm) will be performed using the excavator simulator (see Section 2.3.1 for a description of the simulator) with a ghost arm to give position feedback. Operator performance will be measured with each HMI in terms of both time and fuel. The tasks performed will also be varied (point-to-point motion, tracking, path following, and each of the previous with obstacles added) to investigate how the task parameters change the operator's intent. The mistakes operators make for all experiments will be recorded to determine their fuel and time cost and to investigate possible control algorithms that could be developed to mitigate or eliminate them. Finally, the ghost arm will be implemented on a 3DTV to test if this technology makes ghost arms feasible for teleoperation of more complex hydraulic machines.

3.1 Ghost Arm

A ghost arm will be added to the screen on top of the simulated environment. The ghost arm is kinematically connected to the Phantom. The operator commands the position of the ghost arm with the Phantom. The position of the ghost arm is the position input given to the system, and the excavator servos to the input location. A comparison will be made between this interface, a coordinated rate control interface, and a standard two-joystick interface (for a baseline comparison). The comparison will include measuring how much soil operators remove during a trenching task, how much fuel they consume, and how many mistakes they make.

3.2 How Operators View Their Intent

Operators will be asked to perform several types of tasks (positioning, path following, and tracking) with and without obstacles. While performing the tasks, operators will be asked how they view their intent. Their responses will be used to determine how different task factors affect the way operators view their intent. Also, the operators' responses will be compared to the way the tasks are described to the operator to see if there is a correlation between them. Operator performance will be measured to determine if giving the operator feedback of the same type as the way that say they view their intent increases performance.

3.3 Operator Error Quantification

The errors operators make with different HMIs will be quantified to investigate if operators perform best with feedback of the same type as the input. Operators will be instructed to move the bucket from its current location to a goal location without hitting any obstacles. The system input and the arm's trajectory will be recorded and examined to determine the types of mistakes operators make depending on the HMI. Control laws will then be developed and tested to compensate for operator mistakes. (For example, lowpass filtering may be used if the commanded rate variations are small to reduce mistakes from operator hand tremor.)

4. CONTRIBUTIONS/DELIVERABLES

4.1 Contributions

Contributions:

- Test proposed theory that operators will perform better with an HMI that provides feedback that matches their intent. If the theory valid, this will give designers a guideline to use when implementing a controller.
- Determination of the types of operator mistakes induced by position or rate control and control methods to counteract these errors
- Test for how certain task factors influence the operator's intent
- Measure the influence on fuel economy of some HMIs
- Analysis of 3D ghost arm feasibility with today's technology

4.2 Deliverables

Deliverables:

- Quantification of the different types of mistakes induced by position or rate control and the cost in time and fuel of these mistakes
- Quantification and cost of the different types of mistakeswith control methods to counteract operator mistakes
- Design law for HMIs regarding the type of feedback that should be given
- Measures of fuel efficiency and time efficiency for HMIs implemented
- Excavator simulator with dynamic models of the mechanical and hydraulic system and of the environmental interaction

4.3 Timeline

Timeline for proposed research:

	July 2011	A	S	O	N	D	Jan 2012	F	M	A	M	J	J	A
Add ghost arm to simulator														
Test operator performance with position/rate/ghost arm control														
Analyze results for efficiency and mistakes														
Propose control methods to remove/mitigate mistakes														
Test control methods to mitigate above mistakes														
Test operators' performance to determine how the operator views their intent														
Implement 3D TV														
Test feasibility of teleoperation with 3D TV														

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