Assigned Responsibility for Remote Robot Operation

Nicolas J. Small **Graham Mann** **Kevin Lee**

Applied Artificial Intelligence Laboratory, School of Engineering and IT,
Murdoch University,
Murdoch 6150, Western Australia, Australia
Email: `n.small, g.mann, kevin.lee@murdoch.edu.au`

Abstract

The remote control of robots, known as teleoperation, is a non-trivial task, requiring the operator to make decisions based on the information relayed by the robot about its own status as well as its surroundings. This places the operator under significant cognitive load. A solution to this involves sharing this load between the human operator and automated operators. This paper builds on the idea of adjustable autonomy, proposing Assigned Responsibility, a way of clearly delimiting control responsibility over one or more robots between human and automated operators. An architecture for implementing Assigned Responsibility is presented.

Keywords: Assigned Responsibility, Teleoperation, Automation, Robotics, Adjustable Autonomy

1 Introduction

Due to their resilience and variety in size, tool, and instrument carrying capability, remotely operated robots are suitable for many tasks involving dangerous actions in hazardous environments. These include post-disaster search and rescue (Casper & Murphy 2003) and deep sea maintenance (Lin & Kuo 1997). As well as for gathering data or imagery, the use of such machines is justified by the need to prevent loss of human life and the reduction of cost of operations (Fong & Thorpe 2001, Rehnmark et al. 2005). These vehicles are often only partially autonomous, and thus require additional or full control by one or more human operators.

This variability in the balance of control between human and automated operators is characterised by scales such as *levels of automation* (Sheridan & Verplanck 1978). These scales range from full human control over the robot, to full automatic control, with a variety of intermediate control schemes in between.

At the human control end of the scale, Teleoperation requires the user to make control decisions based on the information relayed by the robot about its own status as well as its surroundings. Often this information is limited in quality and quantity, placing operators under significant cognitive load during the control task. Some setups face the opposite problem, as sensor-heavy robots can provide enough information to overload their operator. This has lead to task specific displays being designed in order to make the use of multiple sources of information more effective and efficient (Nielsen et al. 2007, Nielsen & Goodrich 2006).

At the other end of the scale is full automation of the robot, a difficult task in unstructured environments where the automated robot must have the ability to make control decisions based on its surroundings. While progress in automation is being made, fully automated robots still do not possess the range of capabilities seen in teleoperated robots. The center of the scale includes a variety of approaches, such as support for human input in automated systems, and humans and robots working as equals in teams (Goodrich & Schultz 2007).

This paper focuses on supporting the management of teleoperation tasks, where a single operator is controlling one or more robots. The concept of Assigned Responsibility is introduced with the aim of combining the endurance of automation and the ingenuity of human operators, assigning each tasks that suit them to maximise effectiveness and efficiency. This address issues with both low-level teleoperation, where the operator is unable to neglect his charge, and full automation, which can struggle to perform any more than very specialised tasks (Kumar & Mason 2011).

The contributions of this paper are i) Assigned Responsibility for managing teleoperation, ii) an architecture for Assigned Responsibility, iii) and an implementation of an Assigned Responsibility-based human-robot interface. The remainder of this paper is structured as follows. Section 2 reiterates the need for remotely operated robots and highlights the challenges associated with remote operation. Section 3 proposes and justifies Assigned Responsibility and Section 4 proposes a suitable architecture.

2 Shared Control in Remote Robot Operation

Mixing control responsibilities between human and automated operators in any system is a non-trivial task. There can be conflicts between operators, leading to fighting over control (Parasuraman & Riley 1997) when both sides attempt to take control, or inaction when both sides cede control. In the area of remote robot operation, a new series of challenges are superimposed over these existing issues. These need to be carefully considered when designing mixed autonomy remote robot control systems.

2.1 Challenges in Remote Robot Operation

In the context of interaction between the operator (human or automated) and the robot, four challenges

---

Conferences in Research and Practice in Information Technology (CRPIT), Vol. 162, Stefan Marks and Rachel Blagojevic, Ed.

stand out as being of key importance for any solution to the remote control problem.

1. **Limitations in Communications.** Communications links are affected by bandwidth and round-trip time. A lack of bandwidth limits both the quality and quantity of transmittable information. Latency introduces a delay between the issuing of a command and the arrival of feedback from the robot. This delay slows down task execution, the operator having to wait for this feedback before initiating new commands.
2. **Acquisition of Situational Awareness.** Understanding the environment in which the robot is operating is crucial to making control decisions. In traditional control scenarios, the operator is able to see a vehicle directly in its environmental context (e.g. a person driving a car), or the environment is very well known (e.g. a factory floor). Unlike these, remote control tasks rely on feedback from sensors mounted on the robot which may be inadequate to provide sufficient situational awareness.
3. **Translating Operator Intent to Machine Commands.** The translation of operator intent into commands to the robot needs to minimise disparity between what the operator wants the robot to do and what the robot actually does. The operator needs to have a clear understanding of how their intent is translated to low-level commands; some systems requiring more detailed operator input.
4. **Physical Capabilities.** For robots to replace direct human involvement, they have to be able to accomplish the same tasks. This requires strong and dextrous manipulators, appropriate sensors, sufficient battery life, and controllability.

2.2 Humans and Automation

Humans and automated systems display relatively complimentary aptitudes. Understanding these differences is useful when employing both side by side.

The presence of a human in teleoperation setups provides more advantages than a simple reduction in programming complexity. A human operator possesses experience of the world and how to interact with it, and the ability to solve new problems. These abilities lend teleoperation many desirable characteristics such as robustness and adaptability, and the potential to operate in unexplored environments. Another benefit to having a human in the control loop is the potential to learn skilled action from a human expert, delivered directly to the machine in real contexts (Mann & Small 2012).

Automated systems do not suffer a lot of the problems that face human operators. Factors such as stress, fatigue, and frustration simply do not affect such systems. While these systems lack the creativity and experience of humans, they are suited to performing long, repetitive, and potentially boring tasks that humans find hard to execute competently. These tasks also tend to be the easiest to automate.

2.3 Adjustable Autonomy

Ideally, automated systems will improve to the point where they can operate at full efficiency in any environment. Fully capable automatic control of robots is a desirable end goal, albeit one currently infeasible for many scenarios.

Table 1: Levels of Autonomy for Assigned Responsibility

Mode	Full Name	Description
H	Full Teleoperation	The human operator controls every aspect of the teleoperation process.
H/A	Assisted Teleoperation	The human operator controls the teleoperation process, but is assisted by simple automated systems. For example inverse kinematic control of a robotic arm.
A/H	Human Assisted Automation	The automatic controller executes low-level robot controls. The human operator provides high-level help such as designating waypoints in navigation tasks, and object location in manipulation tasks.
A	Full Automation	The automatic controller has full control.

In the short term, the merging of automation techniques and teleoperated control promises more compelling results. This is understandable when the capabilities and shortfalls of both automated and teleoperated control are compared. The lack of creativity and environmental understanding displayed by automated control systems is compensated for by the inclusion of a human operator in the loop. Repetitive tasks which stress and tire human operators are usually automatable. One such approach to including human operators in the loop is *adjustable autonomy.*

While originally motivated to allow human controlled systems to deal with the long latency of extra-terrestrial teleoperation, adjustable autonomy is defined as the capability of an autonomous system to have its level of autonomy changed during its operation (Dorais et al. 1999). The available levels of autonomy are implementation specific, but can usually be described as a series of modes, ranging from full automation to full human control, with appropriate levels in between. For example, (Goodrich et al. 2001) used four discrete modes in their implementation of an adjustable autonomy system: full autonomy, goal-biased autonomy, waypoints and heuristics, and intelligent teleoperation. These modes were set manually by the human operator during runtime.

3 Assigned Responsibility

If the most desirable solution for remote robotic operation is full automatic control, it makes sense to view the current paradigm of robotic control in unstructured environments (Teleoperation or Teleoperation with automated aids) as a stepping stone towards that solution. It follows that we should not focus solely on improving teleoperation, but on facilitating its replacement while still providing the control required to perform tasks in the field.

This paper proposes Assigned Responsibility as a form of adjustable autonomy-based teleoperation that allows the selective inclusion of automated control elements at key stages of a plan's execution. Just like other shared control systems, the motivation behind this approach is to lessen the cognitive load, stress and fatigue on human teleoperators with the introduction of automated control aids. Assigned Responsibility strives to do this in a way that supports and encourages the gradual automation of the execution of the full task. To do this, Assigned Responsibility relies on pre-planning the execution of

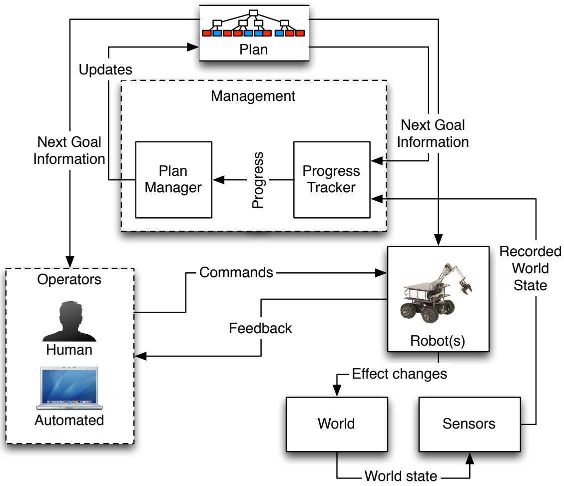

Figure 1: Proposed Architecture for Assigned Responsibility

a task, explicitly assigning subsections of that task to either human or automated controllers. This clear, pre-determined separation of roles is key to avoiding conflicts in an environment with several operators. The cost of this approach is some lack of dynamism in response to unforeseen problems.

3.1 Plans as Trees, and Goal Breakdown

In many fields (e.g. automated planning), a plan is represented as a graph in which the nodes are goals (the individual steps), the edges between then are actions, and goals are defined as desirable states of the world (Ghallab et al. 2004). Achieving a goal amounts to choosing and then performing actions that are required to change the state of the world from an undesirable state to the desirable state specified by the goal. The plan is a tree of interdependent goals, with each parent goal relying on the fulfilment of all its child nodes. A task is accomplished when the root node (the highest-level goal) is satisfied.

These tree representations are useful for Assigned Responsibility, as they are easily describable using graph theory, which provides useful rules to read and understand these graphs automatically. To allocate tasks to either the human operator or automated control system, it is necessary to break down the top level goal into sub-goals, and those sub-goals into further sub-goals until a satisfactory goal granularity is obtained. The resulting plan graph possesses the properties of an ordered rooted tree, namely:

- It can be defined as a connected acyclic graph G with $G = (V, E)$ where V is a collection of n vertices and E is the collection of $n - 1$ edges.
- The vertex (V_1) is designated as the root of G.
- The parent of a vertex is the vertex connected to it on the path to the root; every vertex except the root has a unique parent.
- A child of a vertex V_n is a vertex of which V_n is the parent.
- An ordering is specified for the children of each vertex.
- A terminal vertex (or leaf) of a tree is a vertex of degree 1.

We can interpret these as follows:

- The root is the overall goal to achieve, each other vertex is a sub-goal.
- To achieve a particular sub-goal, its children have to be satisfied, in order.
- By extension, once all sub-goals are satisfied, the root goal is also satisfied.
- The leaves are the lowest-level goals, and are the only goals satisfiable directly. Satisfying all of the leaf goals, in order, satisfies the root goal.

The plan tree graph also has the advantage of being very human-readable, trees being a natural way for people to break down tasks. This allows the human operator to be very clear about the plan.

3.2 Levels of Autonomy and Responsibility Assignment

Being a type of adjustable autonomy, Assigned Responsibility needs to handle various levels of autonomy. By applying the general theories put forward by (Miller & Parasuraman 2007) to the domain of teleoperation, and Sheridan and Verplanck's (Sheridan & Verplanck 1978) automation scale, a set of generic levels of autonomy for use with Assigned Responsibility was created, as described in Table 1.

In Assigned Responsibility each of the plan's sub-goals are explicitly assigned one of these levels before the execution of the plan. It is assumed that the human operator is capable of effectively controlling the robot and satisfying all of the goals using it, and that the preference is to relinquish most of the control to the automated modes in order to free up the human operator. The assignment process is described below:

1. All of the goals are set to "H", full teleoperation.
2. Each leaf goal known to be at least partially automated is set to the appropriate level (Preference goes A, A/H, H/A, H). As the automated system is taught how to accomplish more goals, more and more of the leaf goals can be assigned automated levels.
3. The resulting list of goal and associated assignments is shown to the human operator who then gets the final word on assignment.
4. The final assignment is set, ensuring both the human operator and the automated control system are aware of their responsibilities.

This clear delimitation of responsibilities is useful for two reasons. i) Ensuring that each operator is aware of their responsibilities before execution reduces issues of confusion over control responsibility, a problem in shared control systems (See Section 2). ii) In scenarios where the use of automation is restricted due to laws, safety regulations, ethical considerations, or simple mistrust in the capabilities of that automation, the ability to specify what is and what isn't automated becomes desirable.

4 Proposed Architecture for Assigned Responsibility

Assigned Responsibility is designed to be retro-fitted onto an established teleoperation setup, adding a management module to the pre-existing operator-robot loop. This module does not interrupt the loop, being solely responsible for managing the mode changes and keeping track of progress (See Figure 1). This retro-fitting approach makes this architecture well suited to a modular implementation. The role of this architecture is to provide a framework for these modules to operate in, setting requirements for each module regarding what they can and cannot do, as well as what, and with who, they need to be able to communicate. There are three modular software components: operation, management, and execution.

The operation components are charged with commanding the robot(s) through the accomplishment of the goals they have been set. The plan is made available to the operators during runtime for consultation. On the other side of the control loop, the robot's role is the same as in a normal teleoperation scenario, although the management module may need to access its sensors.

The management module is concerned with both tracking plan accomplishment progress as well as ensuring the plan structure is updated with that progress. It is made of two separate components, a progress tracker, and a plan manager.

1. **Progress Tracking.** Managing the change of operator between subgoals requires a clear understanding of what has been accomplished previously, to both trigger the change, and to provide context to the operator beginning their time in control. This tracking must be done independently of the operators to ensure continuity in the tracking regardless of operator capabilities. This module monitors the world, using data provided by sensors, for the changes expected to occur when each goal has been accomplished. The module then updates a central plan-tracking structure with the progress made. Our first implementation has already been published (Small et al. 2013).

2. **Plan Management.** Component-based systems need centralised sources of information to synchronise each component's understanding of the state of the overall system. In this case, the plan structure is a repository for this system state, and serves to inform each component of plan progress to date, next goal to execute, operation responsibility (See Section 3.1 for more details). This plan structure needs to be updated regularly to be of use, requiring a dedicated plan managing component.

5 Conclusion

This paper proposed Assigned Responsibility for robot teleoperation, an architecture designed to allow the careful allocation of robot control tasks between human and automated operators. This clear delimitation of responsibilities is paramount to ensure that problems linked to mixed autonomy systems such as conflicts between operators are avoided. The architecture also allows support for the gradual automation of robot control tasks, rendering it future proof and well suited to support that gradual automation process. Future work will consist of a complete usability evaluation of the system in realistic maintenance task scenarios.

References

Casper, J. & Murphy, R. (2003), 'Human-robot interactions during the robot-assisted urban search and rescue response at the world trade center', *IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics)* **33**, 367–385.

Dorais, G., Bonasso, R., Kortenkamp, D., Pell, B. & Schreckenghost, D. (1999), Adjustable autonomy for human-centered autonomous systems, *in* 'Working notes of the Sixteenth International Joint Conference on Artificial Intelligence', pp. 16–35.

Fong, T. & Thorpe, C. (2001), 'Vehicle teleoperation interfaces', *Autonomous robots* **11**(1), 9–18.

Ghallab, M., Nau, D. & Traverso, P. (2004), *Automated Planning: Theory & Practice*, Elsevier.

Goodrich, M. A. & Schultz, A. C. (2007), 'Human-robot interaction: A survey', *Foundations and Trends in Human-Computer Interaction* **1**(3), 203–275.

Goodrich, M., Olsen, D., Crandall, J. & Palmer, T. (2001), Experiments in adjustable autonomy, *in* 'Proceedings of IJCAI Workshop on Autonomy, Delegation and Control: Interacting with Intelligent Agents', pp. 1624–1629.

Kumar, V. & Mason, M. (2011), Are we even in the game?, *in* 'Berlin Summit on Robotics 2011: Conference Report', Berlin, pp. 16–24.

Lin, Q. & Kuo, C. (1997), Virtual tele-operation of underwater robots, *in* 'IEEE International Conference on Robotics and Automation', Vol. 2, pp. 1022–1027.

Mann, G. A. & Small, N. J. (2012), Opportunities for enhanced robot control along the adjustable autonomy scale, *in* 'Proceedings of the Fifth International Conference on Human Systems Interaction', Perth, Western Australia.

Miller, C. A. & Parasuraman, R. (2007), 'Designing for flexible interaction between humans and automation: Delegation interfaces for supervisory control', *Human Factors: The Journal of the Human Factors and Ergonomics Society* **49**(1), 57–75.

Nielsen, C. & Goodrich, M. (2006), Comparing the usefulness of video and map information in navigation tasks, *in* 'Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction', pp. 95–101.

Nielsen, C., Goodrich, M. & Ricks, R. (2007), 'Ecological interfaces for improving mobile robot teleoperation', *IEEE Transactions on Robotics* **23**, 927–941.

Parasuraman, R. & Riley, V. (1997), 'Humans and automation: Use, misuse, disuse, abuse', *The Journal of the Human Factors and Ergonomics Society* **39**(2), 230–253.

Rehnmark, F., Bluethmann, W., Mehling, J., Ambrose, R., Diftler, M., Chu, M. & Necessary, R. (2005), 'Robonaut: the 'Short list' of technology hurdles', *Computer* **38**(1), 28–37.

Sheridan, T. B. & Verplanck, W. L. (1978), Human and computer control of undersea teleoperators, Technical report, MIT Man-Machine Systems Laboratory.

Small, N. J., Mann, G. & Lee, K. (2013), Goal accomplishment tracking for automatic supervision of plan execution, *in* 'Proceedings of the 2013 Australasian Conference on Robotics and Automation', Sydney, Australia.