Teleoperation and Collaborative Control*

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Abstract. This paper discusses teleoperation systems and introduces new collaborative control approach that provides complete location independent and facilitates collaboration among group of humans and machines that are geographically distributed. The aim of having collaborative control is to support access, control, monitor, negotiate, coordinate and cooperate functionalities to enable efficient, robust teleoperation in unknown, unstructured and dynamic environments. This system allows human operator to access, interact and control a single or multiple remote operational sites while collaborating with other operators or machines in achieving a common goal. The introduced concept supports multi level control with seamless transfer between them along with different level of command abstraction. It also, focuses on ways to reduce human workload and cognitive fatigue by having a better way to present remote site information. Also, try to ensure situation awareness for effective error and failure recovery, and reduce the impact of the communication time delay and maintain low communication bandwidths by requesting only relevant sensory information about the remote facilities.

1 Introduction

Current state of technology has not yet produced fully autonomous robots/machines that can successfully perform variety of tasks, and has the ability to perceive, move and act in unstructured, unknown and dynamic environments where it is deemed complex, costly and too dangerous for actual human presence. Such autonomous systems are unlikely to be realized in the near future. Therefore, in the context of teleoperation, only partial autonomy in the system can be expected, with tasks allocated between machine and human operator, i.e., there is still strong need for human intervention to configure the remote site for new tasks, and to respond to unanticipated situations [1,10-12,17].

Teleoperated system with components (manipulators, mobile devices, equipment, software systems, and other facilities) are typically developed and used for extending the ability of human to perceive, reason with and perform actions in an environment that is too distant, hazardous, dangerous, uncomfortable, limiting, repetitive, costly or otherwise accepted as being inaccessible for humans [1, 3-6,10, 20]. It represents a true harmonic association of human and machine with human operators act as controllers with decision-making capabilities under dynamic environmental circumstances of remotely located systems which serve to extend the human's sensory perception and manipulative abilities into hostile and hazardous environments with accuracy and dexterity. Undersea, space, and nuclear industry applications benefit substantially from these capabilities and have historically driven most of the research in teleoperation and telerobotics.

Application areas of teleoperated systems may include [3, 9, 10-14, 20] process control plants, underwater, space, resource industries, medical, construction, civil security, etc. The most important common characteristic of these different application areas is that most of them are highly variable and involve operating in unstructured, partially structured, unknown or dynamic work domains. These are defined as classes of environments in which the system surroundings at the remote site cannot be known and modeled in advance with sufficient precision. These tasks require a highly flexible and intelligent control mechanism through well balanced and coordinated human-machine interaction [3,13].

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An ideal system to perform these tasks at remote sites would be one that has the same capability as a human to recognize what task has to be performed and what steps should be taken to carry out the task, and which has the flexibility to perform physical manipulations like the human. In general, current teleoperation implies continuous perceptive and cognitive of human operator involvement in the control of remotely teleoperated system to decide how task should be carried out.

There is a growing need for humans to perform complex, large scale, remote operations and to extend the intelligence and experience of experts to distant applications. But, involving human operator continuously at low level of the task will have its negative impact in affecting his performance. Therefore, there is a need to improve speed and quality of problem solving and to have a better control strategy that enhances the performance of complex systems and distributed processes through a collaborative approach among team members (human operators and facilities) that constitute the teleoperated system. Along the need for an efficient control strategy with control coordination and smooth transfer of control, other primary constraint that should be considered is the communication link and its impact on generating intelligent actions and system reliability [9].

The general goal of this work is to elevate teleoperation to a new level of task performance capabilities by improving the functionality, operability and usability of a remotely operated system. This paper introduces new collaborative control approach that provides complete location independent and facilitates collaboration among group of humans and machines that are geographically distributed. The aim of having collaborative control is to support access, control, monitor, negotiate, coordinate and cooperate functionalities to enable efficient, robust teleoperation in unknown, unstructured and dynamic environments.

2 Efficiency and Complexity of Teleoperation Systems

Generally most of current teleoperated systems consists of a single human operator/user at the local site and a single process/device at the remote site. An operator interacts and handles only one remote device in a direct and continuous tracking that leads to reduce his capacity to perform other task and accordingly affect his work efficiency. At the same time, the process/device at the remote site will continuously wait for new commands from the operator. When remotely operating complex mechanisms in unstructured environment, the task to interact and control them will be difficult for the operator. The difficulties will be enormous when the remote mechanisms tend to have a large number of degree of freedom to control while interacting with task environment. When the communications time delay between the local and the remote sites is large, there will be additional difficulties that affect the performance of the operator. Also, having more sensors carried by the machine/robot and the environment at the remote site, leads to more amounts of data to be processed or judged by the operator. This causes to deepening the communication and fatigue problems and leading to less efficiency.

The instability at the remote site due to the delay can be avoided by using a move-and-wait strategy. This strategy is very inefficient in terms of operations time because during the round trip time the mechanism is typically idle.

Additional parameter that will add its own difficulties beside other related issues (such as, coordination, cooperation, resource sharing, conflicts, deadlock, etc.), appears when more that one human operator try to access and share same or distributed working space, while interacting and controlling a large and complex mechanism, an individual devices or distributed facilities in order to realize an individual task or working collaboratively to realize a shared goal. Also, communication delay makes such task hardly feasible and focuses on the need to have a useful guidance for the operators to fulfil task requirements and enhance safety of overall system,

To enhance human operator interaction with complex systems there is a need to find ways that minimize the impact of communication delay and bandwidth constraints, and develop methods for understanding and modeling human capabilities, limitations, performance, and reliability, as part of the overall engineering and design optimization of complex systems

3 Teleoperation System and Control Modes

Different control modes had been used to control teleoperated system. Such control modes have been classified into control levels based on the role given to human operator and the system at the remote site that include task environment with its facilities. However, human-machine relationship often proves to be inefficient and ineffective, and researchers have continuously been working to have a better control paradigm that governs such relation efficiently. Some of the available control modes are:

Direct control: This mode of control requires continuous human operator involvement where he directly controls actuators at the remote site at all time. Such approach binds completely system's capabilities to human operator skills, and subjects the system to human constraints.

Direct Control with some Intelligent Support: When some of intelligent functions become available at the remote site, human operator may be able to teach the remote system some basic and simple knowledge functions about the remote task environment, such as defining regions that should not be entered. Computer assisted teleoperation and shared compliant control fit into this type.

Reflexive control: Having reflexive control capability embedded with the remote system to free the operator from details of the lower level control concerns associated with direct teleoperation.

Shared Control: Human operator is responsible for controlling some variables or subtasks while the remote system simultaneously control others. The task instructions is shared between direct and autonomous control, where each complement the deficiency of the other and tasks can be interchanged dynamically. In this control type, human act as a supervisor with respect to the control of some variables and directly controls other variables.

Traded Control: Human and machine are consecutively responsible for subtasks, that is, at one time the remote system is in complete control and at other time human is in full control. Human assumes control from time to time. An example of traded control would be navigating autonomously to a target position, while the human operator taking control for the final maneuvers.

Supervisor Control: For teleoperation over large distances such as in space and undersea applications, the time delay makes direct control difficult if not infeasible, and the supervisory control is used instead. Sheridan [16] describes supervisory control as a mixture of direct control and autonomous control, where the autonomous operations are performed under human supervision. Supervisory control also implies circumstances in which human communicates at a symbolic level with the remote machines, providing it with directions but not continuously controlling it. It allows the machine to make decisions under limited conditions. Supervisory control approach will be useful when the autonomous behavior is trustworthy, the task execution time is larger than the delay time, and the unpredictable aspects of the remote environment are changing slowly.

4 Teleoperation and the Internet

The Internet has increased our teleconnectivity by allowing us to electronically connect places and exchange text, graphics, images, sound, and video with anyone whose interest we share, professionally and socially, and virtually anywhere in the world. The Internet and the World Wide Web (WWW or the Web) provide low cost and widely available media rich interface that can make teleoperated resources accessible to a broad range of users regardless of geographic location. The Web is ideally suited to easy data access independent of the underlying operating system and system architecture. It allows for a more structured organisation of information, live update, and easy access.

The Web interfaces are useful to access data through any distributed mission. Any member of a team can participate and interact through a multimedia environment with other team members and with machines that constitute a teleoperated system from any place in the world independent on time and space. Accordingly, ubiquitous Internet as a viable medium for remote systems has generated great interest. Many users are looking for more interactive solutions in which they can actually control and monitor experiments or processes remotely using a Web browser.

The primary constraint in using the Internet to support teleoperation is the communication link. In particular, limited bandwidth directly restricts the quantity and quality of information available to the operator for decision making. Also, the bandwidth over the Internet varies greatly, depending on communication technologies and network load. Additionally, transmission delay affects the reliability of remote operation. Beyond a certain delay, direct control of the remote system may become highly error prone or impractical.

Using the Web as a base for teleoperation arises numerous research issues and concerns. For example, data transmission through the Internet is often irregular and unreliable. Under the Internet, the route followed by data packets is not fixed, and the time required to cross the network can not be guaranteed, with possible loss of data. Consequently, the system must be designed to handle potentially unbounded delay or loss of data. Thus, the amount and type of information that can be exchanged between the remote system and a human operator is severely limited. In spite of that there are many advantages introduced by the Internet and the Web. Accordingly, two Web based approaches in can be considered in supporting teleoperation field:

1. Using the Internet as information dissemination environment in which the main operational local site of a teleoperated system is linked to the Internet in two ways. One between the local site and the remote task environment and the other with distributed team members to disseminate continuously information synchronously and synchronously through a Web browser. Such approach enables team members beyond the local operational site to monitor, access, discuss information and give their feedback to the main operational local site and other team members without engaging in a direct control of the remote system. This will have the advantage in reducing operational cost by having all team members co-located at centralized operation facilities.
2. Have complete sharing control working environment either on centralised process/facilities or distributed one according to the role of each team member. Both human and machine can be considered as a team member for this purpose.

5 Teleoperation and Collaboration

Collaboration can be defined as the creation of shared understanding [23]. Also, collaboration is a fundamental part of an effective decision making and problem solving in complex environment. There are three fundamental reasons for cooperative work between people [24] in which this work is trying to reflect them also for the relation between human and machines and between machine and machine:

1. Augmentative: when there is too much work for one person to achieve in terms of size and capacity, such as lifting a heavy object,
2. Integrative: integration of different techniques and expertise, as in concurrent engineering, and
3. Debative: debate among different perspectives, as in scientific discourse.

In collaborative environments, researchers/users/operators multiply their output through synergistic cooperation while reducing hardware costs through improved equipment sharing to perform task and to achieve common goals. In addition, they improve operational efficiency and quality by distributing knowledge functions such as information processing and enabling parallel performance of operations.

Communication and collaboration can take place over varying dimensions of time and space. Also, collaborating among team members can vary depending on the degree of their interdependence.

The high cost and the uniqueness of research and experimental facilities, the availability of other resources and human experts in terms of time and space, and environmental conditions in many application fields are powering and supporting the direction to have distributed teleoperation systems. Such system allow different users with similar or different qualifications and expertise that are geographically distributed, to collaborate by means of interactivity in the preparation, performing and evaluation of research, test, integration, observation, maintenance, diagnosis, or any other task. The task can be carried out using one or more remote facilities, and the related information can be processed and retrieved as needed. This focuses on the need for teleoperation systems that are adopting collaborative control paradigm that enable them to operate flexibly and robustly in difficult environment, in spite of poor communications, and with high performance regardless of variations between operators.

6 Concept for Collaborative Control

The use of Intelligent entities (devices, mobile robots, systems) at one or several sites and network technology to set up ubiquitous autonomy with behavioral system integrating distributed systems and enabling these systems and human operators to communicate and overcome restrictions of distance. Collaborative control more closely resembles a team consists of humans and machines that communicate and cooperate to achieve shared goal independent on time and geographical location. For this purpose, a machine can be device, robot, equipment, software system and any other facilities. The basic issue of such systems is the structure of the operational team that is making it. Both humans and machines with some level of autonomy are considered members of the operational team. Some of team members can be co-located and the others are distributed over different locations. The control of a single facility or process (may include several machines and humans) at one site can be shared between different team members located at different sites. Three levels of interactions are considered possible among distributed operational team members. These levels of interactions are human to human, human to machine, and machine to machine interactions. Human team member should be integrated as an inside part of the teleoperated system architecture with his powerful creativity, cognition, perceptual and problem solving capabilities, i.e., having the operator augmented into the system. This leads to have quality systems that are capable to respond, interact flexibly with dynamic environments and develop new behaviors as required while insulating human from the hazards at the work environment. Such structure support different level of control with seamless transfer between them. The collaborative control approach defines a role for each team member and accordingly assigns authority for decision-making capability within the overall control structure. Cooperative relations among team members can be dynamic. Communication, negotiation, and coordination toward achieving intelligent actions at a distance should inspire cooperation. When there is a dispute among participating members of team at specific control session in selecting suitable action among a group of actions, a voting mechanism can be applied to optimize the selection process. A team member that holds higher role at that instant can judge the final result. Members in the team should not apply their decision-making authority according to their role before engaging in a constructive dialogue with other team members. Such decision-making authority can be used to resolve deadlock that is blocking the whole operation of the system and to resolve conflict that is affecting the safety and the integrity of the remote facilities and task environment.

7 The Features of the Required Control Strategy

Some of the required control features that need to govern the relation among team members of a teleoperated system can be listed as below:

1. The user interface should be able to control complex mechanisms which allows an unsophisticated operator to comprehend the current and past state of the remote system quickly, to plan and review high-level commands to the remote system, and to send those commands for the remote system to execute them. To take advantage of the highest bandwidth sensory channel available to a human operator, and to encode the information in the most natural manner possible.
2. The need for modular user interface that support and integrate different levels of control and enable human operator to seamlessly interacts with the remote system and its environment in all range of available control between supervisory and direct teleoperation control modes.
3. Building a completely generic teleoperation application is not feasible. Therefore, the need will focus for a generic architecture to be shared by different applications with each domain or between classes of domains. The application architecture should show some degree of dynamic configurability, in order to accept different system configurations that can easily adapted and optimized for a particular system environment without requiring major rework. Such architecture should make the integration of the real facilities easy like a plug-in module with the application domain.

4. Increasing the level of autonomy of the remote systems, to enable and allow the teleoperated system perform tasks without motor inputs from the human. The human role in such control structure will be monitoring and commanding.
5. Provide tools to deal with unexpected events, such as dynamic changes in the remote environment, and unanticipated situations.
6. The system should have the ability to recognize any deadlock or danger or when an unknown situation arises that may constitute emergency or danger. It should inform human operator about it and enable him to engage in a direct control seamlessly to overcome that situation.
7. Time delays is present to some extent in every teleoperation system and this create difficulties in the presentation of both visual and force feedback to the operator, and have largely prevent the widespread usage of direct teleoperation in space and underwater applications. New methods should be developed to overcome the effects of time delay in direct teleoperation. Also, there is a need to design new approaches that minimize bandwidth usage, use the predicted display efficiently with augmented reality, provide sensor fusion capability, and optimize human-computer interaction.
8. With reference to point 7, increasing the artificial intelligence residing at the remote site in order to reduce both the amount of communication between local and remote sites and the demands on the operator. Operator fatigue can be reduced too while still enabling user to take over control at any time.
9. The need to engage humans and machines in constructive dialogue, not merely simple interaction, to exchange ideas and to resolve differences. This leads to the necessity to have a framework in which human and machines can work together and can jointly solve problems. Dialog leads to coordinate and negotiate a better solution or decision and find a way to cooperate in implementing it.
10. Supporting task and facilities distribution along with human operators independent on geographical location and enable collaborative work that lead to realize shared goals.
11. Interactive exception handling aid will be necessary to help the remote site to ask for assistance from the human operator, or to enable human operator to check or interfere with the ongoing remote site functions at its detail level.
12. The interface design must provide obvious opportunities for action on the part of the operator and must be tailored around the operator’s activities at all levels of interaction.
13. Having the ability to adjust autonomy level of the remote site through human operator based on task and remote environment requirements.

8 Working Through Time Delay and Limited Bandwidth

8.1 Sensor fusion

For complex situations related to the increase in number of sensors and the amount of sensory information, the resulting workload can be extremely high and leads directly to fatigue, stress and inability on human operator to perform other tasks. To overcome this and enhance operational efficiency, sensory information for each segment of a task can be presented dynamically in a way that enables human operator to perceive the remote environment quickly and improve situational awareness by fusing data from the related sensors. This will lead to reduce the cognitive overload for the operator, leaving his mental resources to concentrate on the task itself and will be reflected positively on the bandwidth requirements too. Better operational quality can be achieved if the sensors and the fusion method are selected dynamically at a higher level of abstraction based on the requirement of the task to be performed, this will add flexibility and ease the work.

8.2 Images and change update

Communication bandwidth is a significant factor in limiting the transmission of visual data over digital communication lines. It is not necessary to keep continuous quality of feedback data during the whole lifetime of a task. Accordingly, it can be of great help to have adaptable frame rate from the vision system, selecting a dynamic image resolution according to the demand of the task, or using image intelligent compression devices that can reduce the bandwidth demand.

Another way that can reduce the amount of feedback data and consequently the impact of time delay can be achieved by stopping sending streams of image files from the remote site. Instead there is a need to have the ability to recognize any change that may happen between two successive images of the same scene and decide to send the detected moving/changed part of the new image if any. Also, another alternative can focus on sending the area of interest within specific image by specifying a suitable window that mask that area.

8.3 Supporting different command levels

The efficiency of any control strategy related to a teleoperated system is proportional the quality of sensory feedback returns per command that sent from human operator to the remote system. This will have its focus on the number of commands required to implement specific behavior or measurement at the remote site. If the available commands structure within the system includes only primitive and simple commands. Then, expectation will be to send many commands in order to achieve specific goal or behavior at the remote site. While considering the separation between each command that represent at least one round travel time, the higher number of commands sent from human operator, the more impact of communication delay on the efficiency and the performance of the system. Therefore, a better solution to overcome this issue can be achieved by having different command levels of abstraction, i.e., to have a range of primitive and high level commands. High level commands may consist of several primitive commands depending on the target behavior that constitute them. The operator interface should support both high and low level commands, to maximize operator flexibility in sending efficient command sequences as needed. Also, it should enable human operator to interfere at the details that constitute a high level command during its execution and at any time.

8.4 The use of augmented reality, graphical representation and predictor display

Augmented reality is a variation of virtual environments, and it allows users to see the real world through the creation of virtual reality of the task environment using previously acquired sensory data. Such virtual information of the real scene can be visible on operator screen. The use of previous sensory data minimizes the impact on the bandwidth necessary for communication. Also artificially generated graphical displays have been used to enhance depth perception for teleoperation. Commands may be previewed and simulated in the environment prior to sending them to the vehicle. Predictor display overlays on the delayed camera images have often been used to tackle the delay from the remote site. Predictor displays typically keep errors to within certain bounds by virtue of resetting the predictor to the most recent known state, obtained from time-delayed telemetry data. The model is then run much faster than real time, until the point at which a prediction is needed. Thus, the error will never be larger than that which can accumulate during a single run of the prediction model.

9 Conclusions

Web based collaborative control approach that support geographically distributed teleoperation system has been presented. The structure of operational team allows the membership of both humans and machines. The collaborative control aims to reduce the impact of communication delay on human operator and teleoperation system performance. It reduces the need for continuous human involvement while enabling interaction appropriate for a given situation. Collaborative control helps balance the roles of operator and machine. Collaborative control allows the use of dialogue to improve human-machine interaction and enables control flow to be dynamic, flexible, and adaptable.

When constructing an actual teleoperation system, it is necessary to balance autonomous functions that a machine at a remote site should have with the available constraints on communication path. This demands for the need to have an efficient architecture that supports greater autonomy at the machine level. Also, it should provide greater interactivity, safety through an active interface and safeguarding autonomy. Higher-level abstraction commands that are available at the operator site are advantageous. Human operator should be able to intervene at the primitive levels of high level commands at any time needed during their execution.

Mobile agent technology need to be considered to support dynamic level of autonomy configuration at any remote site that will lead to minimize communication delay and improve performance.

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