Preliminary Results in Sliding Autonomy for Coordinated Teams

Jonathan Brookshire, Sanjiv Singh, and Reid Simmons

Robotics Institute Carnegie Mellon University
5000 Forbes Avenue, Pittsburgh, PA 15213-3890
[brookshire, ssingh, reids]@cmu.edu

Abstract

We are developing a coordinated team of robots to assemble structures. The assembly tasks are sufficiently complex that no single robot, or type of robot, can complete the assembly alone. Even with a group of multiple heterogeneous robots, each adding its unique set of capabilities to the system, the number of contingencies that must be addressed for a completely autonomous system is prohibitively large. Tele-operating a multiple robot system, at the other extreme, is difficult and performance may be highly dependent on the skill of the operator. We propose and evaluate an implementation of a framework that, ideally, provides the operator with a means to interact seamlessly with the autonomous control system. Using an architecture that incorporates sliding autonomy, the operator can augment autonomous control by providing input to help the system recover from unexpected errors and increase system efficiency. Our implementation is motivated by results from an extended series of experiments we are conducting with three robots that work together to dock both ends of a suspended beam.

Introduction

Increasingly, robotic systems perform tasks that humans cannot accomplish in environments where humans cannot operate. Search and rescue, manufacturing, construction, and planetary exploration are examples of the complex tasks and the hostile environments in which robots are expected to function. The intricate nature of these tasks may require a team of robots capable of monitoring and guiding their own progress with a high level of autonomy. On the other hand, unpredictable environments and circumstances may exceed the abilities of the autonomous system and, as a result, also demand tele-operator intervention or assistance. In this way, a system that combines elements of both autonomy and human control becomes necessary to assure performance and quality.

Our primary objective is to develop fundamental capabilities that enable multiple heterogeneous robots to work together, and with humans, in flexible, robust ways to deal with contingencies and to improve overall efficiency. The basic concept is for robots to accomplish tasks, either autonomously or through tele-autonomy, which can be mixed and matched together to achieve significant levels of coordinated behavior. Decisions about when to switch between autonomous and tele-operated control can be made smoothly, both by humans and by the robots themselves.

This concept, which we term *sliding autonomy*, addresses one of the main areas of difficulty in current human-robot interaction: Typically, control is highly inflexible, reflecting an “either-or” command constraint. That is, operating structures are either pure tele-operation or pure autonomy. As complexity of a task increases, so does our inability to anticipate every contingency in which the robot will find itself (Bruemmer 2002). In order to overcome these further complexities it is necessary to consider a mixed initiative system in which humans are able to collaborate seamlessly with a team of robots. Further, although autonomous operation is important for teams of robots performing complex functions, there will be many situations in which the robots will not successfully perform, or not even know how to perform, a given subtask. In addition, it is impossible to anticipate the types of failures that might occur when a team of heterogeneous agents collaborate and to devise autonomous recovery strategies for all of them ahead of time. In these cases, and others as well, human intervention can help.

As part of developing sliding autonomy, we are designing the architectural framework and techniques that enable a human to take over control of a given subtask, while allowing the rest of the system to operate autonomously. This architecture allows the robot to maintain cognizance of the overall task — monitoring it to determine when it has been completed (in which case it should autonomously move on to the next task) or when it has failed (in which case it should attempt recovery actions, perhaps in concert with the human operator). Figure 1 shows examples of shifting control between an operator and the system. This approach has several distinct advantages over other approaches to human-robot interaction. The robot maintains local autonomy even during tele-operation. In most other approaches, the task context is lost when the robot cedes control. When autonomous control is returned to the robot, it has little idea of what the user has done and how those actions fit into the overall original goals and tasks. Our approach allows a smooth hand-off between (any part of) the system and a human operator. This approach is truly mixed initiative. The robot can request help if it determines it has reached the limits of its range of expertise; but, at the same time, an operator can request to take over control of some task whenever he/she desires.

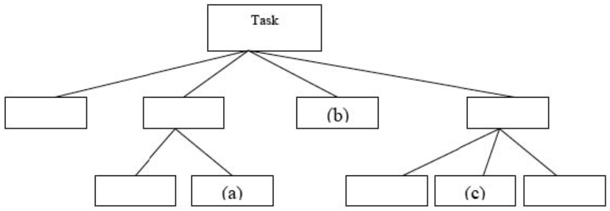

Figure 1 – Mode shift between operator and system. A task is decomposed hierarchically. Control can shift in three instances: (a) human initiated - the operator might take control if dissatisfied with the progress of the system; (b) scripted - a subtask is designated a priori as one to be performed by the operator; the system turns over control to an operator at the appropriate time and picks up operation when the operator indicates completion; (c) robot initiated - the system continuously estimates confidence in its own state and the chance of completing the task; upon encountering low confidence, it autonomously drops down in levels of autonomy and asks for operator assistance.

Related Work

Our architectural approach differs from most other work in multi-robot systems, in which the robots are either loosely coupled agents, with little or no explicit coordination (e.g. Arkin 1992, Donald 1995, Parker 1998, and Mataric 1992) or are tightly coordinated by a highly centralized planning/execution system. Many multi-robot tasks are characterized by close coordination of the robots. One approach is to coordinate the robots centrally (e.g. Chaimowicz 2001 and Khatib 1995). Doing so, however, introduces a single-point source of failure, and does not work well in high latency situations. An alternative approach, somewhat more reliable and flexible, is to distribute control. This remedy, however, makes it difficult to achieve tight coordination. Under our scheme, individual robots can autonomously solve many problems either by themselves or by negotiating with each other, without having to invoke a high-level planner. These characteristics reduce the need for inter-robot communication and improve overall reliability. As such, our approach is similar to work in which coordination strategies are explicitly represented and reasoned (Jennings 1998). Our architecture also supports dynamic team formation. Coordination occurs between agents filling specific roles in the structure of the team, and roles can be dynamically assigned to agents.

In terms of human collaboration with robots, there are several relevant research efforts. The COBOT project seeks to make manually operated machines more intelligent by providing guidance so that the operator does not have to finesse control. Typically, the human provides the force input, while the system steers the mechanism into the right place (Gillespie 1999 and Wannasuphoprasit 1998). A research effort in getting large numbers of people (hundreds) to collaborate to achieve a trajectory tracking task is discussed in (Goldberg 2001). This type of system is essentially tele-operation because the robot is being controlled explicitly. The authors show that variation in performance is based on the number of collaborators of the task. A more closely related system to our own is described by Fong et al. in which the robot and the user participate in a dialogue (Fong 2001). The robot can ask the operator to help with localization or to clarify sensor readings. The operator can also make queries of the robot. This framework assumes that the robot is capable of performing all tasks as long as it has full state information. Another effort has examined the effectiveness of an operator when controlling a robot at different levels of autonomy given increasing inattention to the robot (Goodrich 2001).

Scerri presented an architecture for sliding autonomy with an example daily scheduler (Scerri 2002). The autonomous system attempted to resolve timing conflicts (missed meetings, group discussions, personal conflicts, etc.) among some set of team members. Members could adjust the autonomy of the system by indicating their intent to attend gatherings or willingness to perform tasks.

The term sliding autonomy is interchangeable with *adjustable autonomy* as presented by Dorais et al. (Dorais 1998). The authors provide several examples in which sliding autonomy will be essential for space operations where demands on the operator must be focused and minimized. Using a roving eye and a (fixed) manipulator similar to ours, Kortenkamp et al. developed and tested a software infrastructure that allows for sliding autonomous control of a robot manipulator (Kortenkamp 1999). The task involved a pick-and-place operation during which sliding autonomy allowed the operator to recover from visual servoing errors, participate in high-level planning, and tele-operate to complete tasks beyond autonomous capabilities. Our work extends these experiments with a more complex assembly task and a greater level of sliding autonomy between robotic agents.

Approach

We are testing these ideas in the context of a team of robots that work together to assemble a physical structure, that is, an assembly that requires operations which cannot be performed by any single robot. The robot team includes a mobile manipulator (a skid-steered ATRV with a NASA-developed five degree-of-freedom manipulator), the NIST Robocrane (a six DOF inverted Stewart platform), and a mobile robot equipped with stereo cameras (the roving eye) (Simmons 2000).

Each specialized robot plays a role in docking a beam securely between two uprights. The Robocrane provides the heavy lifting capability and large workspace to grossly maneuver the beam, while the mobile manipulator finely positions the beam into the docking clamps using a coordinated resolved motion rate control to drive the end-effector.

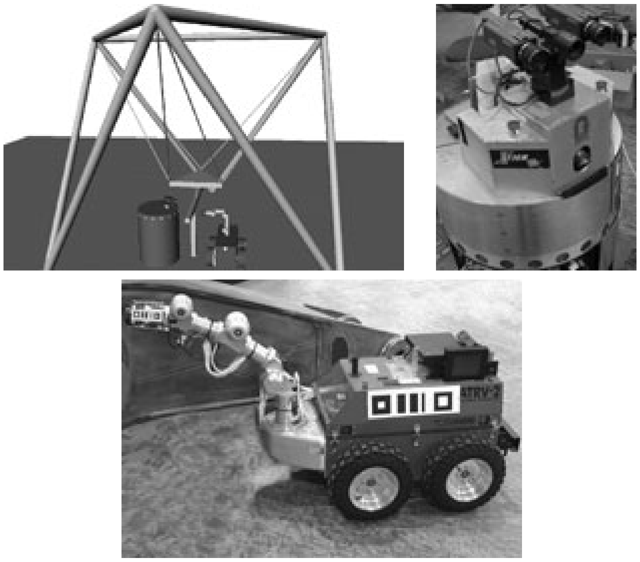

Figure 2 –Experimental test bed consisting of a (top left) six DOF crane, (top right) roving eye, and (bottom) mobile manipulator.

The roving eye provides feedback for visual servoing and can be moved to focus on different aspects of the operation. The beam and the robots are marked with fiducials that allow the roving eye to determine a relative pose between the fiducials. This information is then continually transmitted wirelessly to the two other robots so that they can, in turn, use this information to move. Figure 4 shows the three primary steps to dock both ends of the beam.

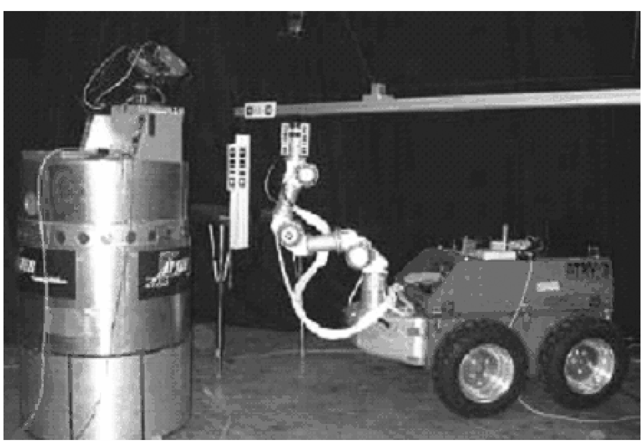

Figure 3 – Tracking fiducials by the roving eye robot. Fiducials are mounted on the fixed structure, on the beam being emplaced, and on the mobile manipulator.

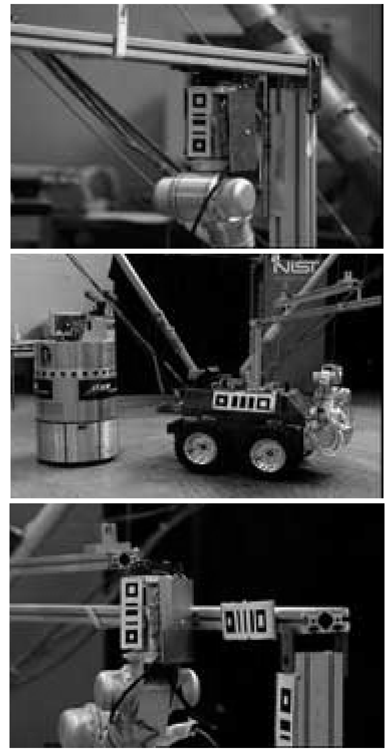

Figure 4 – Steps in the assembly process: Crane brings the beam close to the upright supports. Mobile manipulator grasps one end and docks it in one support. ("near end", top) The mobile manipulator turns around, drives to the second support. ("swap ends", middle) In this case, the mobile manipulator guides the beam in the horizontal direction while the crane lowers the beam into place. ("far end", bottom)

Coordinating these robots requires synchronization of a task tree that spans robots. This is done using a task executive that orchestrates the task across the robots (Simmons 1998). For example, the two-ended beam docking described here requires the execution of the tree shown in Figure 5. The task is complex enough that there are many different failure modes, some of which occur very infrequently. As also illustrated in Figure 1, sliding autonomy describes support at several different levels of operator interaction. These different levels require that each task which may be fulfilled by the operator (e.g., Figure 1 tasks a-c), which is ideally every task, be capable of functioning in both autonomous and tele-operated modes. For example, the task leaf which characterizes the mobile manipulator's dock beam operation sometimes fails to dock the beam securely due to errors in the visual tracking. When the robot initiates human control due to this failure, possibly after some number of re-tries, the dock task must switch modes and accept control from the tele-operator (ignoring inputs from the visual tracking routine). Although the system is performing the same function, docking the beam, the task is accomplished differently in the autonomous and operator modes.

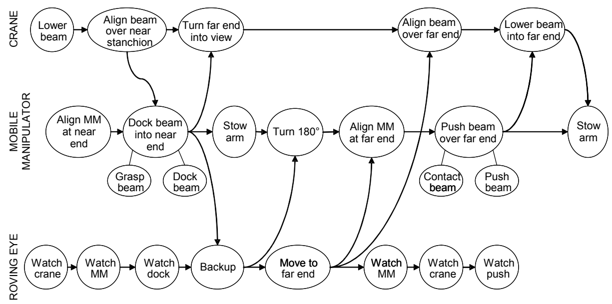

Figure 5 – Task tree that specifies coordination across multiple robots to perform assembly of a beam. Synchronization with the roving eye tasks has not been shown for clarity.

Sliding autonomy has successfully been implemented in several parts of the system and all three modes of human interaction have been demonstrated:

- **preassigned tasks**: Driving the mobile robot around in our construction site is not an easy task to automate. Instead, our system hands control over to the operator with the goal of bringing the mobile manipulator into view of the roving eye. As soon as the mobile manipulator is in view, the roving eye automatically starts tracking and the operator is able to turn control back to the operator.
- **human intervention**: When the roving eye loses sight of one of the fiducials, an autonomous search is started to search the environment exhaustively. The operator can interrupt this search, take control of the roving eye, and manually find the missing fiducial. As soon as the fiducial is picked up, autonomous operation can resume.
- **failure recovery**: In those cases where the robot is stuck and cannot proceed after having tried the preplanned contingencies, it gives up and asks for help. We have tested this case by forcing the system to fail while docking (by blocking the docking clamps). When the mobile manipulator has failed three times, it turns the system over to the operator under tele-operated control.

To validate our hypothesis that sliding autonomy will increase a system's overall efficiency and performance, we have compared fully autonomous, sliding autonomous, and tele-operated versions of the system. Efficiency and performance are quantified by the number of successful completions and the time needed to complete the task. The assembly task has been executed 50 times in each of the control modes.

For the autonomous trials, the system performed the assembly task as described in Figure 4 without any sort of operator interaction (aside from initialization). For the sliding autonomy trials, operators were allowed to intervene and perform a fixed set of tasks. These tasks included grasping, pushing, and docking the beam. The operator could also control the roving eye's visual search and take control of the mobile manipulator at several other times. During these experiments there were no preassigned operator tasks. When an operator intervened during a trial that would have been successful regardless (intervention may have served to accelerate success), we term that discretionary intervention. Intervention during trials that would have otherwise failed is termed mandatory intervention. Finally, for the tele-operated trials, four operators each performed fifteen iterations of the assembly. The primary input to the operator was the roving eye's video stream (i.e., the operators could not directly see the system). The operator output control to each robot using several simple interfaces and a six DOF "space mouse." All operators were familiar with the system, but the skill levels differed (one skilled, two intermediate, and one novice). Each operator was allowed to perform several practice runs and the extreme performances were discarded for a total of 50 trials.

Results

Over the 50 trials, the fully autonomous system had a 64% successful completion rate (see Figure 6). The failures occurred roughly evenly across the near end, swap ends, and far end segments of the experiment. For example, on very few occasions there was an electrical failure on the mobile manipulator that prevented movement. Errors in the visual servoing nearly caused a collision between two of the robots. A handful of times, a portion of the assembled structure broke apart and prevented further assembly, the roving eye irrecoverably lost sight of some fiducial, or some autonomous task failed to start properly. The nature and variety of errors does not clearly suggest a small or easy set of autonomous fixes. Yet, from the standpoint of a passive observer, the majority of these cases had a clear recovery solution. Considering the experiment where two robots nearly collided, the proper strategy would be to recognize the close proximity, stop before the collision, and back up one of the robots. Averting this situation autonomously might require increased visual accuracy, better motion control, or more complex obstacle avoidance. Although there is undoubtedly the potential to remedy this kind of error autonomously, for some systems the high cost of implementation seems to out weigh the 2% improvement in success rate. The timing results are described in Table 1.

	Successes	Completion Times	
		Mean	Std-dev
Fully Autonomous	64%	10m	1.5m
Sliding Autonomy	94%	10m	2m
Discretionary Only	68%	9.5m	1.5m
Mandatory Only	26%	11m	2.5m
Tele-operated	96%	12.5m	4m

Table 1 – Comparison of success and timing characteristics for trials. Mean are standard deviation are calculated based only on successful trials.

During the sliding autonomy trials, operator failure handing was never employed (in all cases the operator intervened before exceptions were generated). The overall success rate jumped to 94%, with only three failed experiments. The three failed experiments involved damaged hardware (proximity switches necessary for grasping were damaged) and two cases where erratic mobile manipulator movement (possibly the result of network failure) required a software halt. Strictly speaking, the erratic movements were recoverable with operator intervention, but we chose to power cycle the equipment for safety reasons.

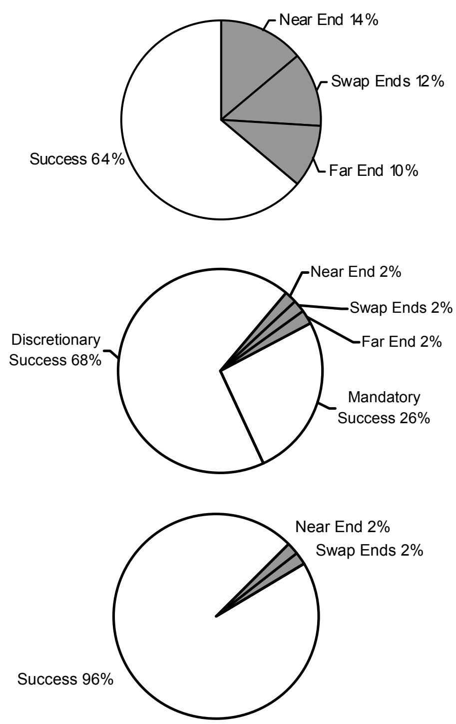

Figure 6 – Success and failure results from fully autonomous (top), sliding autonomous (middle), and tele-operated (bottom) trials. "Discretionary Success" trials are sliding autonomy trials that were successful with discretionary intervention. "Mandatory Success" trials were sliding autonomy trials that were successful only with mandatory intervention. Shaded wedges represent failed trials; empty wedges represent successful trails.

For the sliding autonomy trials, the average completion time was similar to that of the fully autonomous system, but the standard deviation was higher (see Table 1). On close consideration, however, this average and standard deviation are not directly comparable to those of the autonomous runs. The operator is now able to recover from disastrous runs that would not have weighed into the autonomous averages. Indeed, the successful trials must be subdivided into two groups: discretionary intervention and mandatory intervention. Of the original 50 runs, 68% were discretionally successful – a number that compares with the 64% autonomously successful rate. The small decrease in average time (see Table 1) over the autonomous runs is the result of the operator intervening to quicken autonomous tasks. One common point of intervention was manual completion of the autonomous visual search. Of the original 50 runs, 26% were successful only with mandatory intervention with an average of 11 minutes and a standard deviation of over 2.5 minutes. The large standard deviation is representative of the difference in the various errors. When the operator simply had to move the roving eye to bring a fiducial back into view, the time penalty was small. When the operator had to reposition robots to reconstruct parts of the assembly that had fallen apart, the time penalty was much larger. From these results, it is clear that there is a substantial increase in successful runs and a small, but noticeable, time decrease in the discretionary intervention trials. The success of the mandatory trials accounts for the increase in successful runs, but the completion of those tasks placed a heavy load on the operator.

The tele-operated runs demonstrated a high success rate similar to that of the sliding autonomy trails, but there was a significant increase in execution time. With an average of 12.5 minutes and a standard deviation of 4 minutes, operators took longer to complete the task with less reliability. The types of errors experienced involved irrecoverable hardware errors similar to those in the sliding autonomy trials.

Future Work

Qualitatively, the addition of human operators endowed the system with the ability to handle a much wider variety of exception situations. The implementation of a single operator interface module could potentially compensate for several autonomous error recovery modules. Operator's responses from the tele-operated trials suggested that the operators were most comfortable performing rough alignments and moving robots between locations. Tasks that required fine movements and a great deal of depth perception (i.e., visual servoing) tended to be more difficult and tedious. For example, during tele-operated trials, the time to complete the first grasp and dock operation was far longer than that of the autonomous system. On the other hand, moving robots from the first to second dock locations was much faster for the human system. It is not clear at this time whether this consensus was the result of an unsupportive interface or a fundamental difference in control schemes.

In future work, we would like to categorize tasks for which manual operation is most efficient and, then, determine how those tasks can best be allocated between the operator and autonomous system. Future experiments will also attempt to enhance the feedback provided to the operator with the intent of improving the fine manipulation abilities. This enhancement may be in the form of a 3D reconstruction of the robot environment using fiducial information already available from the roving eye. Even without this enhancement, evidently a well suited system would focus the autonomous system's capabilities on visual servoing and the operator's capabilities on gross robot positioning and error recovery.

Future experiments will also increase the complexity of the assembly task. In doing so, we hope to show that our results indicating the advantage of sliding autonomy and our architecture are scalable. The new experiments will include operations that require operator assigned tasks, increased visual servoing, possibly more robotic agents, and repeated grasp-and-dock operations.

Conclusions

Systems that rely solely on autonomy suffer from unexpected complications and excessive complexity. Tele-operated systems suffer from latency, bandwidth, and human limitations. Our goal had been to develop sliding autonomy into an architectural framework that allows an operator to meaningfully and seamlessly participate in control of a multi-robot system. Our experiment included the assembly of a beam and two nodes using three distinct robots. The assembly procedure could be completed both autonomously and with tele-operation, but the experimental results have shown marked improvement – in both efficiency and performance – by using a sliding autonomous version of the system.

Acknowledgements

The authors acknowledge the help of Brad Hamner, Brennan Sellner and Myung Hwangbo to get the team of robots to be operational.

References

Arkin, R. Cooperation without Communication: Multiagent Schema-Based Robot Navigation. *Journal of Robotic Systems*. 9:3, pp. 351-364, 1992.

Bonasso, P.; Kortenkamp, D.; Miller, D.; and Slack, M. Experiences with an Architecture for Intelligent, Reactive Agents. *Journal of Artificial Intelligence Research*. 9:1, 1997.

Bruemmer, D. J.; Dudenhoeffer, D. D.; Marble, J. Dynamic Autonomy for Urban Search and Rescue. *AAAI Mobile Robot Workshop*, Edmonton, Canada. August, 2002.

Chaimowicz, L.; Sugar, T.; Kumar, V.; and Campos, M. An Architecture for Tightly Coupled Multi-Robot Cooperation. In *Proceedings International Conference on Robotics and Automation*. Seoul, Korea, May 21-26. 2001.

Donald, B. Distributed robotic manipulation: experiments in minimalism. In *Proc. International Symposium on Experimental Robotics (ISER)*. Springer-Verlag, pp 11-25, 1995.

Doty, K. and Van Aken, R. Swarm robot materials handling paradigm for a manufacturing workcell. *In IEEE ICRA*. Volume 1, pages 778-782, 1993.

Dorais, G.; Bonasso, R.; Kortenkamp, D.; Pell, P.; and Schreckenghost, D. 1998. Adjustable autonomy for human-centered autonomous systems on mars. Presented at the Mars Society Conference.

Fong, T.; Cabrol, N.; Thorpe, C.; and Baur, C. A Personal User Interface for Collaborative Human-Robot Exploration. In *Proc. International Symposium on Artificial Intelligence, Robotics, and Automation in Space*. Montreal, Canada. June, 2001.

Fong, T.; Thorpe, C.; and Baur, C. Robot, Asker of Questions. In *Robotics and Autonomous Systems*. Vol. 42, 2003.

Gillespie, R.; Colgate, J.; and Peshkin, M. A General Framework for Cobot Control. *International Conference on Robotics and Automation*. Detroit, MI. 1999.

Goldberg, K. and Chen, B. Collaborative control of robot motion: Robustness to error. In *International Conference on Intelligent Robots and Systems (IROS)*. 2001.

Goodrich, M.; Crandall, J.W.; and Stimpson, J. L. Neglect Tolerant Teaming: Issues and Dilemmas. In proceedings of the *2003 AAAI Spring Symposium on Human Interaction with Autonomous Systems in Complex Environments*.

Goodrich, M.; Olsen, D.; Crandall, J.; and Palmer, T. Experiments in adjustable autonomy. *In Proceedings of IJCAI Workshop on Autonomy, Delegation and Control: Interacting with Intelligent Agents*. 2001.

Hägele, M.; Schaaf, W.; and Helms, E. Robot Assistants at Manual Workplaces: Effective Co-operation and Safety Aspects. *Proceedings of the 33rd ISR (International Symposium on Robotics)*. October 7-11, 2002.

Hershberger, D.; Burridge; Kortenkamp, D.; and Simmons, R. Distributed Visual Servoing with a Roving Eye. *In proceedings, IROS*. 2000.

Jennings, J. and Kirkwood-Watts, C. Distributed mobile robotics by the method of dynamic teams, *In Proc. Conference on Distributed Autonomous Robot Systems (DARS)*. 1998.

Khatib, O.; Yokoi, K.; Chang, K.; Ruspini D.; Holmberg, R.; Casal A.; Baader A. Force Strategies for Cooperative Tasks in Multiple Mobile Manipulation Systems. *Intern. Symposium of Robotics Research*. Munich, October 1995.

Kortenkamp, D.; Burridge, R.; Bonasso, P.; Schrenkenghoist, D.; and Hudson, M. An intelligent software architecture for semi-autonomous robot control. In Autonomy Control Software Workshop, Autonomous Agents 99, 1999.

Parker, L. ALLIANCE: An Architecture for Fault Tolerant Multirobot Cooperation. *IEEE Transactions on Robotics and Automation*. 14:2, pp. 220-240, April, 1998.

Mataric, M. Distributed Approaches to Behavior Control, In *Proc. SPIE Sensor Fusion V*. pp. 373-382. 1992.

Scerri, P. and Pynadath, D. Towards Adjustable Autonomy for the Real World (2002).

Simmons, R. and Apfelbaum, D. A Task Description Language for Robot Control. *In Proc. Conference on Intelligent Robotics and Systems*. Vancouver, Canada. October, 1998.

Simmons, R.; Singh, S.; Hershberger, D.; Ramos, J.; and Smith, T. First Results in the Coordination of Heterogeneous Robots for Large-Scale Assembly. In *Proceedings International Symposium on Experimental Robotics*. Dec 2000, Hawaii.

Simmons, R. Structured Control for Autonomous Robots. *IEEE Transactions on Robotics and Automation.* 10:1, pp 34-43, February, 1994.

Wannasuphoprasit, W.; Akella, P.; Peshkin, M.; and Colgate, J.E. Cobots: A Novel Material Handling Technology. *International Mechanical Engineering Congress and Exposition*. Anaheim, ASME 98-WA/MH-2, 1998.