Information Management as the Key to Emergency Management

Position Paper

Paul Scerri (pscerri@cs.cmu.edu)

Robotics Institute
Carnegie Mellon University

A variety of new sensing technologies are quickly maturing enough to be practically useful for emergency management applications. Such technologies range from autonomous robots, satellites, sensor networks and facilities for civilians to provide information. While the utility of these sensors to understanding the emergency situation is clear, the sheer volume of information generated presents a novel challenge to organizations to manage, process and effectively use that information.

Unfortunately, while the quantity of information available to emergencies managers is likely to exponentially increase over time, the ability to communicate and process that information is not increasing at the same rate. Wireless communication bandwidth is pushing up against fundamental limits. Computers and agents have an almost unlimited ability to process information but humans have cognitive limitations that limit the amount of information they can consume, regardless of the elegance of the interface. One of the key challenges for any organization is to work out how to move that information around the organization to ensure that those who need it get it, without overwhelming individuals with huge volumes of information.

If managed well, new information streams should dramatically improve an organizations ability to act towards its goals, but it is not clear that more information will *necessarily* lead to better performance. At the simplest level, needing to deal with too much information might paralyze an organization. Moreover, there is much existing literature showing that typical information flow through an organization is far from optimal and can lead to a range of much bigger problems. As organizations become flatter, the use of intelligent, information processing systems becomes more widespread and more information comes into the organization, we can expect new phenomena to emerge. Of particular concern are emergent pathologies that are only seen at the system level. We hypothesize that some recent, highly public failures by organizations to correctly fuse large volumes of, in retrospect and on balance, correct information may be partly due to the organizations inability to manage the information. The initial mis-assessment of the impact of Katrina and the expectation of finding WMDs in Iraq are two possible examples of this.

Our research is focused on how large, heterogeneous teams of humans, robots and intelligent, information processing agents process and manage large volumes of noisy, conflicting and perhaps even intentionally misleading information. We are pursuing three threads of research, related to this problem. First, we are looking at models of how information moves around different organizational structures and what synergies and pathologies can occur. Second, we are developing algorithms that maximize the efficient use of constrained bandwidth in getting large volumes of information to the members of the organization that most benefit from it, even when the roles and tasks of team members are changing dynamically and are not known to all the team. Lastly, we are looking at interface design issues that allow operators to make effective use of large, information collecting robot teams. In the following sections, we briefly describe some of the key results and open questions on each of these threads.

Dynamics of Large-Scale Information Sharing

Large heterogeneous rescue management teams will often be in situations where sensor data that is uncertain and conflicting is shared across a peer-to-peer network. Not every team member will have direct access to sensors and team members will be influenced mostly by teammates with whom they communicate directly. We have investigated the dynamics and emergent behaviors of a large team sharing beliefs to reach conclusions about the world. We found empirically that the dynamics of information propagation in such belief sharing systems are characterized by information cascades of belief changes caused by a single additional sensor reading. The distribution of the size of these avalanches dictates the speed and accuracy with which the team reaches conclusions.

A key property of the system is that it exhibits qualitatively different dynamics and system performance over small changes in system parameter ranges. In one particular range, the system exhibits behavior known as scale-invariant dynamics, which we empirically find to correspond to dramatically more accurate conclusions being reached by team members. In fact, teams exhibiting belief propagation with scale invariant dynamics can be as much as 50 times more reliable at reaching correct conclusions than teams whose dynamics did not exhibit scale invariance. Moreover, we observed that in the range where the system exhibits scale invariant dynamics, system convergence is much faster than in the other system ranges. Figure 1 shows the relationship between reliability, R, convergence time, Cn, and the conditional probability an agent assigns to communication from its neighbors. While the dramatically increased decision reliability (correctness of the conclusions) makes it highly desirable to have teams exhibit scale invariant belief propagation dynamics, our work predicts that this will occur over relatively small ranges of the relevant system parameters. Minor changes in network structure, conditional probabilities assigned to communications from neighbors and sensor reliability all delicately impact whether scale invariant dynamics occur making it extremely difficult to predict parameter ranges over which scale-invariant dynamics occur.

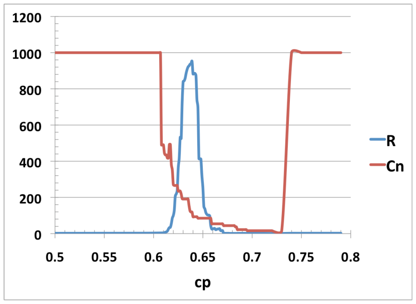

Figure 1: Relationship between conditional probability and reliability and convergence time.

Algorithms for Efficiently Sharing Information

In large, collaborative, heterogeneous rescue response teams, team members often collect information that is useful to other members of the team. Recognizing the utility of such information and delivering it efficiently across a team has been the focus of much research, with proposed approaches ranging from classic flooding, gossiping, and channel filtering. Interestingly, random forwarding of information has been found to be a surprisingly effective information sharing approach in some domains.

We investigated this phenomenon in detail and showed that in certain systems, random forwarding of information performs almost half as well as a globally optimal approach. Figure 2 shows how close simple random information passing can perform relative to an optimal policy that is infeasible in practice. Using order statistics, it is possible to place an upper bound on average case performance of information sharing in large teams. In certain cases, random policies achieve a significant portion of that performance, and by adding simple heuristics to avoid redundant communication, it is possible to further improve their performance. Thus, in domains whose network and utility distributions approach these cases random information sharing policies may present an efficient and robust information sharing solution. Furthermore, this performance is scale-invariant by design, making these policies particularly well suited to large team environments. Overall, random policies seem to perform relatively poorly on small-worlds networks, while performing well on scale-free and lattice networks. In addition, hierarchical networks are ill suited to even optimal token-based information sharing algorithms.

Using this type of analysis, it is possible to evaluate which information sharing methods are best suited to particular domains. By modeling the utility distributions of these domains, it may also be possible to gain insight into fundamental properties of real-world information sharing problems, in turn improving information sharing algorithms. Further graph-theoretic and probabilistic analysis may yield tighter bounds on performance, and additional experiments can determine the optimality of other common information sharing algorithms.

Building on the random propagation, we use simple, local decision-theoretic reasoning to dramatically

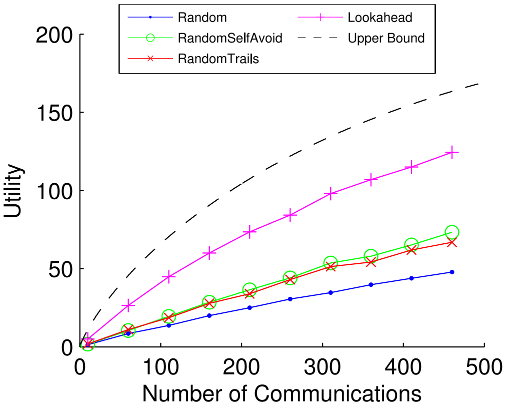

Figure 2: Relative performance of random information propagation versus an optimal policy.

improve performance. A key to the solution is imposing a static network topology on the members of the team where each agent requiring communication to be only along very few links in that network. The key observation underlying this solution is that each piece of information is interrelated and the sender of a piece of information can "guess" who might need some information based on previously sent messages. Thus, when an agent has a piece of in- formation, it can determine which of its neighbors in the network is most likely to either need the information or know who does, based on related messages previously received.

Operator Interfaces for Large Robot Teams

Figure 3: A robot requiring assistance.

Robotic search and rescue teams of the future will consist of both robots and human operators. Operators are utilized for identifying victims, by means of camera feeds from the robot, and for helping with navigation when autonomy is insufficient. As the size of these robot teams increase, the mental workload on operators increases dramatically, and robots may find themselves in precarious situations with no assistance for resolution. We have developed an approach that utilizes multiple levels of autonomy to allow a robot to consider a range of options, including asking for operator assistance, for dealing with problematic situations to maximize efficient use of the operator's time.

The approach relies on individual robots having some capability for understanding that they are in a situation where operator input or tele-operation can be helpful. This self- reflection can be very conservative, flagging more situations that require operator input than are actually difficult for the robot. For example, in this work, robots consider getting operator input when their pitch changes unexpectedly or when they are making no progress toward their goal for some period of time. If a robot decides it needs operator assistance, a request is sent to a *Call Center,* which can pass the request for assistance on to an available operator. The call center prioritizes tasks according to the relative value of the task associated with the robot requesting help. If the wait for an operator's attention is too long, the robot can reason about other courses of action that may resolve its problem. The combination of self-reflection by the agents and the call center to route requests maximizes the efficient use of the operator's time, and improves the overall team utility.

When a robot decides that operator input may be useful, it has a range of possible options, some of which require it to collect information from other agents or from the call center to decide what action to take. For example, before choosing to wait for operator input, the robot needs to know the length of the queue of requests at the call center. The robot also attempts to estimate the length of time the operator will need to help it out of the current situation. Options for the robot include simply giving up its task, getting another robot to take over its task, or getting another robot to provide context to the current situation leading to a de- crease in the amount of time the operator will take to resolve the robot's problem. The outcomes of all these actions are uncertain and the aim is to maximize overall performance, hence MDPs are a natural choice for representing the reasoning.

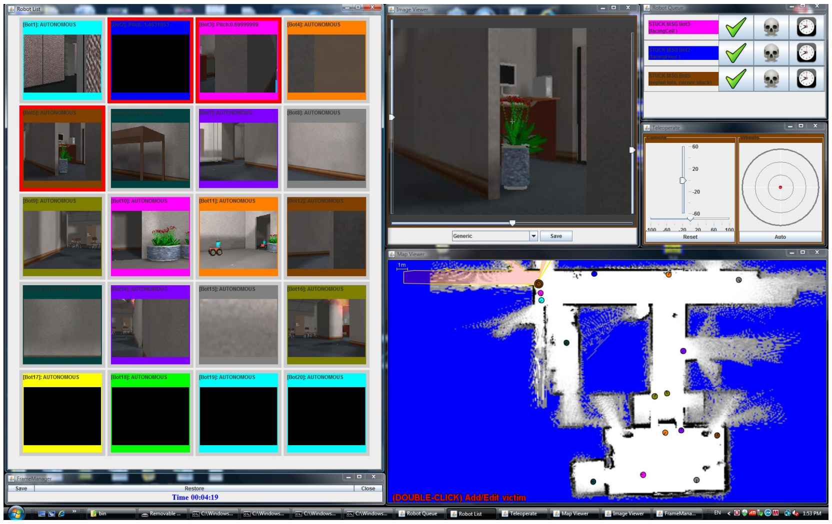

Figure 4: User interface with Call Center for 20 robots.