Negotiating monitoring task allocation for orbiters

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Abstract. We are interested in the problem of coordination of ground-based control stations and orbiting space probes for allocating monitoring tasks for emerging environmental situations that have the potential to become catastrophic events threatening life and property. We assume that ground based sensor networks have recognized seismic, geological, atmospheric, or some other natural phenomena that has created a rapidly evolving event which needs immediate, detailed and continuous monitoring. Control stations can calculate the resources needed to monitor such situations, but must concurrently negotiate with multiple autonomous orbiters to allocate the monitoring tasks. While control stations may prefer some orbiters over others based on their position, trajectory, equipment, etc, orbiters too have prior commitments to fulfill. We evaluate three different negotiation schemes that can be used by the control station and the orbiters to complete the monitoring task assignment. We use utilitarian and egalitarian social welfare as the metric to be maximized and discuss the relative performances of these mechanisms under different preference and resource constraints.

1 Introduction

Recently there has been a research initiative to coordinate between Earth-based sensors (such as a video camera or devices on an ocean buoy) and orbiter missions for efficient monitoring and investigation of a large variety of natural phenomena [1]. Creating operation plans in such distributed settings is especially difficult when so many entities have input. Currently, the activities of a spacecraft are often planned weeks or months in advance for Earth orbiters; thus, these missions are practically unable to respond to events in less than a week. We study the problem of fully autonomous response to emerging, potential natural disasters that require coordination of control stations and earth orbiters for adequate monitoring. We are interested in expediting the response time and accuracy to different rapidly evolving natural phenomenon. Space orbiters are autonomous and have prior commitments and resource constraints which may or may not allow them to take on additional monitoring load at short notice. We assume that orbiters can negotiate between themselves and with ground control centers and can evaluate the utility of an announced monitoring task based on their current schedule and resource constraints. An allocation of a monitoring task between multiple orbiters will have different utilities from the perspective of each of the orbiters and a ground-based control station. We are especially interested in the utilitarian (sum of utilities of all agents) and egalitarian (the utility of the least happy agent) metric of social welfare of such a system. Maximizing utilitarian social welfare in a system corresponds to maximizing the efficiency of the system while maximizing the egalitarian metric corresponds to maximizing fairness in the system.

2 Coordination via negotiation

For most of this paper, we restrict our discussion to one control station negotiating with two orbiters for allocating a fixed number of monitoring tasks given an impending emergency detected by a ground based network of sensors. The overall monitoring task can be divided among the two orbiters by partitioning the total time period into n non-overlapping sets. We now present three alternative negotiation mechanisms we have evaluated for task assignments and briefly discuss their merits and demerits.

Sequential auction: Auction mechanisms [3] can be used to find subtask allocations to maximize social welfare. Due to exponential time complexity of combinatorial auctions, a more feasible, simplified, auction scheme can be to auction each of the n time units sequentially. Suppose the utility to orbiter i for doing the j^{th} unit task is u_{ij} and the corresponding utility to the control station is u^c_{ij}. The control station will award the j^{th} unit task to the orbiter k, where $k = \arg\max_{i \in \mathcal{I}} \{u_{ij} + u^c_{ij}\}$, where $\mathcal{I} = \{1, 2\}$ is the set of negotiating orbiters.

Multi-issue monotonic concession protocol (MC): The orbiters arrange the possible task allocation agreements in decreasing order based on their utilities and propose allocations in that order. If one party finds that the utility of the allocation it is going to propose is as good as any proposal it has already offered, it accepts that proposal, A disadvantage of this protocol is the relatively slow exploration of different possibilities. This can, however, be improved by increasing the amount of concessions made at each step.

Mediator-based simulated annealing: Another distributed approach to task allocation is proposed by Klein et al. [2], where the negotiating parties try to improve on the current proposal. A simulated annealing scheme is used to search for better proposals where the current proposal is used as the starting point. In this approach, a mediator proposes an allocation offer [3], and the negotiating parties either accept, or reject the offer. If all of the parties accept the offer the mediator generates a new proposal by mutating the current offer. Otherwise, the

[3] The mediator initially generates this offer randomly.

mediator generates a new proposal by mutating the most recently accepted offer. The search terminates if any mutually acceptable proposal is not generated by the mediator for a fixed number of proposals.

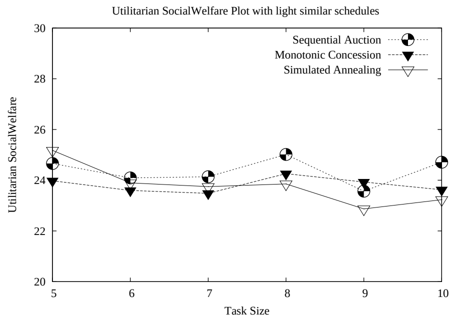
3 Logistics of the system

Each orbiter is capable of sending pictures of different quality (q). We assume that u_i^τ, the utility that the orbiter receives in the form of payment for any time unit τ is proportional to the quality of service. Orbiters have a current schedule S_i, a vector of preassigned tasks for a finite horizon. We represent the vector S_i as $\{S_i^\tau\}^{l(S_i)}$ where $l(S_i)$ is the the total length of time for which the orbiter has preassigned tasks. The utility for S_i given by μ_{S_i} is a distribution of u_i^τ over $l(S_i)$ while the utility distribution of task t given by μ_t is a distribution of u_i^τ over $l(t)$. A proposal made by an orbiter is a vector $P_i \in \{P_i^\tau\}^{l(t)}$ where $P_i^\tau \in \{0, 1\}$. Next, we need to define an allocation α as the set $\{\alpha^1, \ldots, \alpha^{l(t)}\}$, where $\alpha^\tau = i$ if the time unit τ of the monitoring task has been assigned to orbiter i. We assume that the utility of an allocation is characterized by the following factors: the orbiter prefers to allocate the same task for consecutive time periods; performing a new task (a task not allocated before) incurs a overhead cost which is half the value of the utility that the orbiter is supposed to receive for doing the task for that time unit; switching back to a task incurs a penalty that is proportional to the number of time units that elapsed in between. The control station maintains a tuple $V =< p_1, p_2 >$ where p_i denotes the preference of control station for orbiter i.

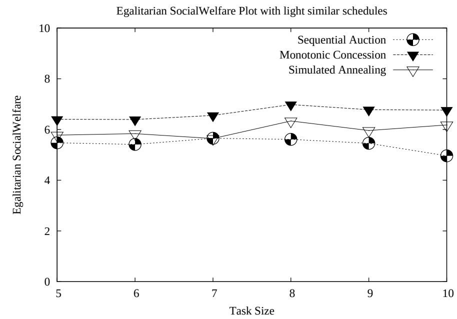
4 Experimental Section

In our experiments, we assume that μ_t and μ_{S_i} can be approximated by the function $f_\zeta(x) = \psi_\zeta \times 1/(\sqrt{(}2 \times \pi) \times d_\zeta) \times e^{-(x-m_\zeta)^2/2\times d_\zeta^2}$ with parameters m_ζ, d_ζ and ψ_ζ, where $\zeta \in \{t, S_1, S_2\}$. The values of m_ζ and d_ζ are represented as fractions of $l(t)$. These parameters determine the shape of ζ and we vary them throughout our experiments to obtain different forms of μ_t and μ_{S_i}.

In the first series of simulations, we first tried to evaluate the performance of the three negotiation techniques when both the orbiters have similar light schedules (results in Figure 1): we use $m_{S_1} = m_{S_2} = 0.5$, $d_{S_1} = d_{S_2} = 0.5$ and $\psi_{S_1} = \psi_{S_2} = 0.5$. The values of m_t and d_t for all our experiments are chosen randomly for each run. From Figure 1 we see that for such schedules, the sequential auction approach dominates the other techniques when the metric is utilitarian social welfare while monotonic concession does better in terms of egalitarian social welfare. Under such a situation maximizing the utilitarian social welfare for each individual time unit leads to maximizing the metric for all the time units. The corresponding egalitarian social welfare is low as the bulk of the task is allocated to one orbiter to minimize the cost of switching between orbiters. The monotonic concession, does better on the latter metric as



(a) Utilitarian Social Welfare Plot



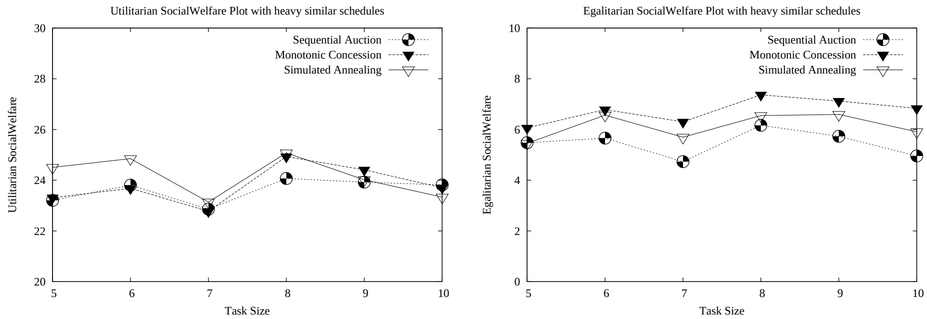
(b) Egalitarian Social Welfare Plot

Fig. 1. Utilities obtained with different negotiating schemes when orbiters have similar light schedules

it supports a more fair allocation by requiring agents to make concessions until the allocation is mutually acceptable.

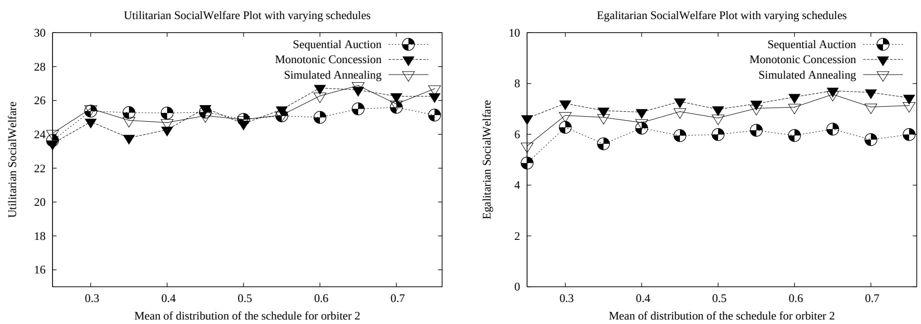
Next, we tried to evaluate the performance of the three negotiation techniques when both the orbiters have similar loaded schedules (results in Figure 2). For this scenario, we use $m_{S_1} = m_{S_2} = 0.5$, $d_{S_1} = d_{S_2} = 0.5$ and $\psi_{S_1} = \psi_{S_2} = 1.5$. Under such a situation, sequential auction is never a better solution which is reflected by its poor utilitarian and egalitarian social welfare values. In such resource constrained situations, the myopic approach of maximizing utility per subtask does not maximize the overall system utility. Mediator based simulated annealing performs best in terms of utilitarian social welfare while monotonic concession continues to provide the highest egalitarian social welfare. In the final simulation of the series, we tried to see the effect on performance of the three techniques when the orbiters schedules vary from being similar to being perfectly complimentary. We use $m_{S_1} = d_{S_1} = 0.25$ and vary m_{S_2} from 0.25 to 0.75 (results in Figure 3). The results show that sequential auction performs the best of the three mechanisms as long as the schedules are somewhat similar (for $m_{S_2} <= 0.5$). The other protocols produce better utilitarian social welfare with the increase in complementarity of the schedules. Monotonic concession continues to dominate in terms of egalitarian social welfare.

In another series of simulations, we tried to study the effect on the utilitarian social welfare of all the three mechanisms with varying m_{S_2} and p_2/p_1 keeping m_{S_1} fixed. Figure 4(a) plots the difference of the utilitarian social welfare of the sequential auction and monotonic concession mechanisms against m_{S_2} and p_2/p_1. Figure 4(b) plots the difference of the utilitarian social welfare of the sequential auction and simulated annealing mechanisms against m_{S_2} and p_2/p_1. In both the plots, it is clear that for a fixed schedule of orbiter 2 (fixed value of m_{S_2}), the value in the z axis shows an increase with increase in the value of p_2/p_1. This suggest that as the preference of control station for one orbiter increases, it is better to use the sequential auction mechanism if maximizing the utilitarian social welfare is the main criterion. The high utility received by



(a) Utilitarian Social Welfare Plot (b) Egalitarian Social Welfare Plot

Fig. 2. Utilities obtained with different negotiating schemes when orbiters have similar loaded schedules

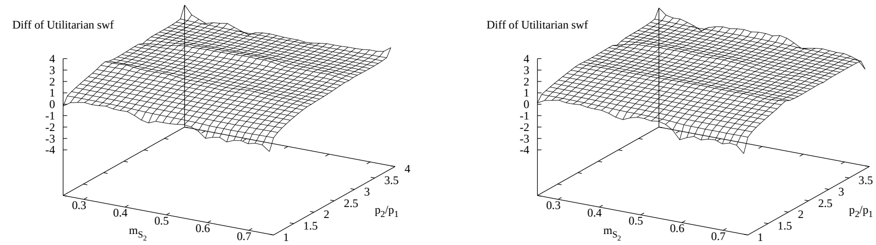


(a) Utilitarian Social Welfare Plot (b) Egalitarian Social Welfare Plot

Fig. 3. Utilities obtained with different negotiating schemes by varying the schedule of the second orbiter

the control station for allocating most of the monitoring task to orbiter 2 is manifested in the high utilitarian social welfare of the system. The value in the z axis stabilizes for $p_2/p_1 \geq 2.5$ hinting that the control station can gain no more with further increasing in its preference for orbiter 2. This trend is true for all values of m_{S_2} (refer Figure 4). But the low value of egalitarian social welfare suggests that gain in total utility comes at the price of loss of utility of one agent. Such allocations will work in practice only if side payments are used by the control station to compensate the deprived orbiter.

To summarize our results, if the chief criterion of mechanism selection is high egalitarian social welfare, then monotonic concession should be the preferred choice. However, if the chief criterion is utilitarian social welfare maximization, then there is no single mechanism that can guarantee high value for all situations. When the allocations for each individual time unit are uncorrelated, maximizing the utilitarian metric for the entire monitoring task is achieved by maximizing the metric for each individual interval, sequential auction performs



(a) Plot of difference of utilitarian social welfare of sequential auction and monotonic concession, varying m_{S_2} and p_2/p_1

(b) Plot of difference of utilitarian social welfare of sequential auction and simulated annealing, varying m_{S_2} and p_2/p_1

Fig. 4. Plot of difference of utilitarian social welfare

better. Unfortunately due to the dynamic nature of μ_{S_i} and μ_t, such a situation is not very common. Mediator based simulated annealing performs better under such circumstances as it provides fair approximations to the global optimum allocation through heuristic search over the entire search space.

5 Conclusion

In this paper we have studied the problem of fully autonomous response to emerging, potential natural disasters that require coordination of control stations and earth orbiters for adequate monitoring. We have compared three different negotiation mechanisms used by the orbiters and the control station to reach an efficient agreement on the allocation of the task. Our objective was to find a robust, fast and efficient negotiation mechanism that enables the orbiters and the control station to quickly reach an efficient and fair agreement. As part of our future work, we would also like to explore if the negotiating parties can adaptively choose the most suitable negotiation mechanism for different emergencies.

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