The ISTeC People-Animals-Robots Laboratory: Robust Resource Allocation

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Abstract—This corresponds to the material in the invited plenary presentation by H. J. Siegel. It is an overview of the ISTeC PAR Laboratory under development, and a summary of some current robust search efforts that are part of PAR.

In the chaotic, time-sensitive environment of a post-disaster search and rescue scenario, making decisions on how to best utilize resources is difficult. Leaders must assign assets (e.g., people, robots, animals, equipment) to accomplish the mission quickly and with minimal loss of life. Their difficulties are compounded by the communication and inter-operability challenges presented by a multi-entity team. The developing ISTeC People-Animals-Robots (PAR) laboratory at Colorado State University will identify and solve the challenges presented by these diverse teams. This multi-disciplinary research group will provide a directed, coordinated environment for the development of the knowledge and competency required to design a good synergistic solution of people, animals, and robots for a given problem. This invited paper provides an overview of the PAR Laboratory and extends a mathematical model of a village search to the search and rescue domain.

Keywords: People-Animals-Robots, robustness, resource allocation, ISTeC

I. INTRODUCTION

This corresponds to the material in the invited plenary presentation by H. J. Siegel. It is an overview of the ISTeC PAR Laboratory under development, and a summary of some current robust search efforts that are part of PAR.

Colorado State University’s Information Science and Technology Center 1 (ISTeC) is organizing the PAR (People-Animals-Robots) multi-disciplinary research laboratory to study how teams of people, animals, and robots can be used together in new, synergistic ways in a variety of environments. The PAR Laboratory group includes faculty from departments such as the Clinical Services Department in the College of Veterinary Medicine & Biomedical Sciences, the Psychology Department and the Computer Science Department in the College of Natural Sciences, the Computer and Information Systems Department in the College of Business, and the Electrical and Computer Engineering Department in the College of Engineering. The anticipation of a significant increase in the number of groups of people, animals, and robots cooperating to solve a problem (e.g., medical/elderly care, disaster management, homeland security, military missions) motivated the creation of the lab. The laboratory goals include: determining how groups of people, animals, and robots can work together in an optimal way; and identifying the mathematical, functional, intellectual, psychological, and sociological interactions within and across groups. The laboratory will form interdisciplinary research teams, and develop knowledge and competency to design good synergistic solutions using people, animals, and robots for a known problem. Furthermore, situations where a disaster has occurred (e.g., an earthquake), the laboratory will develop strategies for using PAR elements to define the problem (e.g., Are there casualties? Are there fires? Is there potential for building collapse?). The PAR Laboratory provides an environment where new and existing coordinated research can occur, leading to innovative solutions for future multi-entity challenges.

Many problem domains exist where PAR teams could cooperate to solve a problem. The unique capabilities of team members, when combined, creates a more flexible and capable team. Animals, such as dogs, provide powerful senses (e.g., olfactory) and the ability to move agilely in difficult terrain. Robots can mount a variety of sensors to gather data, while reducing risk to valuable life forms. For the PAR Laboratory, our definition of robots includes electronic and electro-mechanical devices that may be

1 http://istec.colostate.edu/

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articulated, kinematically redundant autonomous agents or mechanisms, with multiple input sensors and outputs, controlled by a computer (e.g., unmanned aerial vehicles (UAV), packbots [10]). Finally, people in a PAR team are defined as anyone that may need, use or interact with a robot or animal. These people combine dexterous movement with critical thinking to solve problems and manage the total team.

Currently, problem domains exist that use teams of people, animals, and robots and the number of domains will increase in the future. Examples of current domains include mining disasters [13], post-earthquake search and rescue, fire fighting, and military village searches. Each of these environments represents a cluttered and complex environment requiring cooperation among numerous heterogeneous autonomous individuals and teams. In the firefighting scenario of [3], teams of humans and robots cooperate to search and navigate a structure fire while maintaining a coherent team structure.

A model for these scenarios using PAR teams is a complex and mathematically interesting problem. Among the problems in these domains are team member communication and robust resource allocation. A fully inter-operative team requires the capability to communicate in a “natural” manner. A sophisticated Human/Animal/Machine Interface (HAMI) would allow effective communication between team members. For example, the work in [14] describes a network architecture for robotic systems that are tasked to assist humans depart an area under emergency circumstances. These robots are constrained by a requirement to operate with humans in a “natural way”.

How to best utilize the team members to accomplish the assigned task is difficult. Resource allocation heuristics that utilize the concepts of robustness to account for uncertainty in the environment and that model the capabilities of the team types are necessary for efficient and effective use of the PAR elements.

A contribution of this paper is to increase awareness of the potential for using people, animals, and robots together to solve problems. Our first PAR effort is in the area of military village searches. Here a stochastic mathematical model was proposed as the basis for a robust resource allocator. In this paper, we demonstrate how the mathematical model for military village searches can be extended to a post-disaster search and rescue environment.

The remainder of the paper is organized as follows. A review of related work is in Section 2. In Section 3 of this paper, a discussion of the robustness metric developed in [2, 15] is presented. Section 4 summarizes the military village search scenario presented in [12]. The proposed search and rescue model is presented in Section 5, and in Section 6 we present conclusions.

II. RELATED WORK

A lot of research has been conducted in the field of human-robot interaction, robot-animal interaction, and on resource allocation for search and rescue missions. Currently we do not know of any laboratory, other than the proposed PAR Laboratory, that combines people, animals, and robots.

The field of search and rescue resource allocation has a variety of work completed. This work mostly focuses on people and equipment, and generally does not include stochastic models that address robustness.

The authors of [9] developed a resource allocation tool designated ALLOCATE that uses a fitness function based on expected fatalities in a search and rescue scenario. The goal of the work was to allocate people and heavy equipment to work sites to minimize the total number of fatalities for a given scenario. Their method mixes the use of stochastic information (e.g., probability of fatalities, probability of stabilizing a structure for a time interval) and deterministic information (e.g. work rates of resources, size of work areas). Unlike our work, their work uses stochastic information in a limited role. They use the expected value of potential fatalities and not the entire pdf (probability distribution function). More significantly, they do not incorporate robots and animals into the model’s work teams.

In [8], the authors develop a knowledge based, real-time resource allocation tool. They create and test an explicit Problem Solving Model (PSM) for use in a daily search and rescue tasking tool. The PSM uses rules and templates to classify incidents and then develops action plans that match the mission goals. The tool’s purpose is to advise and track SAR (search and rescue) missions. In contrast to our work, they do not use stochastic information to characterize uncertainties, and then derive near optimal resource allocations that are robust against these uncertainties.

Research teams at the Bristol Robotics Laboratory and Carnegie Mellon University are actively researching methods for human-robot communication and interoperability. An example of the work done at the Bristol laboratory is in [19], where the communication methods between humans and robots are examined to improve their interaction. Carnegie Mellon hosts the Project on People and Robots within the Human-Robot Interaction group. It has produced work such as [11] that tries to understand how humans communicate with robots.

Groups like the Oxford University Computing Laboratory are working on projects that develop robot-animal synergies. Their work on the robot sheepdog [20] attempts to develop robots that interact with animals to achieve specific goals – herding sheep.

In our review of related works we were unable to detect any direct animal involvement with both humans and electro-mechanical robots in a coordinated manner. Dogs have long been used for searching in a variety of environments. Dogs and other animals have been used for transporting people and supplies. Robots and mechanized vehicles have taken over some of these tasks, but animals offer certain advantages. For example, small mammals can be trained to go into places robots and/or people cannot go because of size and/or terrain restrictions. We feel that the best solution is to combine the best attributes of animals with
those of robots and people to achieve vital tasks such as building searching and other rescue operations.

III. ROBUSTNESS CONCEPTS

One research area within the PAR Laboratory is robust resource allocation of PAR teams. The definition of robustness is presented in [2] and a methodology to calculate the robustness of a resource allocation is presented in [1, 15, 17]. Robust resource allocation has been studied in a number of systems (e.g., [2, 18, 16]) for a variety of fitness functions.

Before applying robustness to a scenario, one must answer the three robustness questions in [2]. Namely: (1) What behavior of the system makes it robust? (2) What uncertainties is the system robust against? and (3) Quantitatively, exactly how robust is the system? The required behavior for the system to be considered robust may be one of or a combination of criteria, such as a specified time constraint is met, or a specified percentage of fatalities or less occurs. The uncertainties can be the effects of weather, execution time of a task, or any variable whose actual value is unknown at the time a resource allocation is planned. The quantitative measure for robustness can be a user defined fitness function that allows a comparison in terms of robustness of resource allocations (specific examples are in Section IV and V).

The robustness metric for a given resource allocation can be developed using the FePIA (Features, Perturbation parameters, Impact, Analysis) method of [1]. The steps of the FePIA procedure are: (1) identify the performance features that determine if the system is robust, (2) define the perturbation parameters that characterize the uncertainty, (3) calculate the impact of the perturbation parameters on the performance features, and (4) conduct the analysis to quantify the robustness. The FePIA method provides a formal mathematical framework for modeling environments such as military village searches or post-disaster search and rescue scenarios.

We will use the scenario from [15] to illustrate the application of the FePIA method. The performance features are those measurable system attributes that can be compared against the robustness criteria (e.g., the makespan of a set of tasks in a heterogeneous computing (HC) system). A robust system must account for perturbations (e.g., variation in the actual execution time of tasks in an HC environment) and recommend a resource allocation that is robust with respect to these uncertainties. Once the perturbation parameters are enumerated, it is necessary to describe mathematically how they impact the performance features (e.g., how the execution times impact the makespan). The collective effects of the uncertain perturbation parameters on the performance features must then be evaluated to find a robust allocation of assets. For the final step, stochastic (probabilistic) information about the values of these parameters, whose actual values are uncertain, is used to quantify the degree of robustness. The resulting stochastic robustness metric (SRM) [15] is the probability that a user-specified level of system performance can be met (e.g., the probability that a given makespan constraint is met).

The application of the FePIA method to village searches is provided in Section IV. An extension to that example to post-disaster search and rescue is in Section V.

IV. ROBUST MILITARY VILLAGE SEARCHES

Military village searches require the allocation of resources (e.g., humans, military working dogs, explosive ordinance detachments, UAV) to tasks (e.g., building searches) to complete the mission according to its performance objectives (e.g., completion within a specified time constraint). In this environment people, animals, and robots work together to search designated target buildings. This environment is subject to numerous uncertainties (e.g., weather effects on movement and search rates, effects of enemy action, impact of physical fitness on team movement rates) that create differences between the planned completion time and the actual completion time. As a result, the ability to make robust resource allocation decisions that account for these perturbations is highly valued.

In this village search environment, the performance feature is the maximum search resource completion time for the set of search resources, RCT_max, and the system is robust if the mission is completed prior to the mission deadline time (MDT). The time to search a given building is a complicated function of factors that include the building characteristics, search team characteristics, and pdfs of the relevant uncertainties. This will result in a pdf that represents the building search time.

To calculate the time it takes a team to search its assigned buildings, we use the building search time pdfs. In particular, we can convolve (assuming independence) the building search time pdfs for the buildings assigned to that team to generate the search team’s completion time pdf.

For each team, we can use its completion time pdf to calculate the probability of completion prior to the MDT. To do this, we integrate the pdf from time 0 to the MDT and the area under this portion of the pdf is the probability that team i will complete by the MDT.

It is assumed that the search resources have adequate supporting elements to operate independently and therefore the team completion times are independent. Thus, the stochastic robustness metric, SRM, is defined as the product of the probabilities of all the teams completing before the MDT. That is, the SRM is the probability that all resources (teams) will complete by the MDT.

The robustness metric can be utilized in two manners for the village search scenario. In the first manner, a military unit is tasked to conduct a village search within a given time constraint. Here the tool is used to calculate the resource allocation that has the highest probability (SRM) of meeting the mission deadline time.

For the second scenario, a military commander may want to know the minimum time needed to complete the village search mission that can be guaranteed with a given probability (e.g., 95%). In this case, the probability of 95% is the fixed constraint, and the tool attempts to find a resource allocation.
that will minimize the mission completion time with that given probability.

Military village searches are studied for simulation and performance improvement in works such as [4, 5]. Our model for military village searches uses people, animals, and robots, along with stochastic models for the perturbation parameters, to create a robust resource allocation. This model contains numerous similarities to other environments (e.g., search and rescue, disaster recovery) and is easily extended to these environments with a few modifications. This is discussed in the next section.

V. POST-DISASTER SEARCH AND RESCUE MODEL

To apply the robustness procedure to the post-disaster search and rescue scenario, one must first answer the three robustness questions in [2]. In this case, the system is defined as the search and rescue mission with its assigned search resources, target structures, and the environment. The required behavior for the system to be considered robust may be one of or a combination of criteria, such as a specified time constraint is met, having no casualties due to lack of medical treatment, or a power consumption constraint for the search resources. For the development of this example, the robustness criterion is the search deadline time (SDT) or time by which the search mission must be completed.

To illustrate the search and rescue problem, Figure 1 provides an example allocation for a search and rescue scenario. As shown in the figure, the search area is comprised of a set of target structures, $T = \{TS_1, TS_2, \ldots\}$, and a set of movement paths, $M = \{M_1, M_2, \ldots\}$, with associated distances between structures. In the figure, $TS_2$ is a partially collapsed structure and $TS_{11}$ is a completely collapsed structure. The target structures are assigned for search using search resources, $\mathcal{R} = \{R_1, R_2, \ldots\}$, where $R_i$ can represent a human search team, a dog team, a specialized robot, etc. Disaster response planners must allocate the resources (search resources) to the tasks (target structure searches) in a manner that will meet the given performance requirement (search deadline time). A model of this scenario must account for factors such as the search rate of the search resources, the movement time between structures, the ordering of the structure searches, and the perturbation parameters (uncertainty) pdfs.

A system of this type will need to be robust against a variety of dynamic uncertainties that occur in the field. Examples of perturbations in this domain include: the search rate ($SR_i$) of team $i$ under ideal conditions; the effects of precipitation ($P$) on the search rate; the effects of temperature or heat ($H$) on power consumption; trafficability ($TR_i$) effects for movement path $k$ on movement rates (e.g., road surface conditions, flooding, mud). It is assumed that stochastic models can be developed for each of these perturbation parameters ([6], [7]) and that the pdfs can be approximated for experimentation.

![Figure 1. An example resource allocation for a search and rescue mission with three search resources (human team, robot team, and a working dog team) allocated to six tasks (structure searches – intact buildings, partially collapsed building, collapsed building, bridge) with six movement paths.](image)

The impact of the perturbation parameters and the methodology to quantify the robustness metric is described in the following paragraphs. A search area consists of a set of target structures (e.g., intact buildings, collapsed buildings, bridges, tunnels), with a corresponding set of areas, $A = \{A_1, A_2, \ldots\}$. A search resource $i$'s movement rate, $MR_i$, is the rate that the resource can traverse a movement path under ideal circumstances. The subset of target structures assigned to a search resource and the order of search may be constrained by environmental considerations (e.g., accessibility by large equipment, congestion on entry routes) and thus some orderings are invalid. If all parameters are known exactly, the search completion time, $SC_{ijk}$, for resource $i$ searching a given target structure $TS_i$ and traversing movement path $k$ is the area of the structure divided by the search rate, plus the distance of the movement path to the structure divided by the resource movement rate. Because the size of the areas and the movement paths are not exactly known, they are modelled as random variables. The search completion time is a complex function of the perturbation parameters: $A_j$, $SR_i$, $MR_k$, $H$, $P$, and $TR_i$. The perturbation parameters considered...
are random variables. Therefore, the search completion time for team \( i \) on target structure \( j \) and its corresponding movement path \( k \) has a pdf defined as:

\[
SC_{ijk} = f_{SC_{ijk}}(A_i, SR_i, MR_b, H, P, TR_k)
\]  

(1)

The result of equation 1 is a random variable with a distribution consisting of structure search completion times. It is assumed that the pdf for this function will be created at run time using input values for the perturbation parameters (e.g., path trafficability, predicted temperature).

Summing the building completion times for a resource results in the pdf for the search resource completion time, \( SRC_T \), for a search resource, \( R_n \), where \( k \) is the movement path associated with \( T_S \) and \( n \) is the number of target structures in its search set.

\[
SRC_T = \sum_{j=1}^{n} SC_{ijk}
\]  

(2)

For each team \( i \), we can use its completion time pdf, \( SRC_T \), to calculate the probability of completion prior to the SDT, \( P(SRC_T \leq SDT) \). To do this, we integrate the pdf from time 0 to \( SDT \) and the area under this portion of the pdf is the probability that team \( i \) will complete by the \( SDT \).

In this example, it is assumed that the search resource teams are organized at a granularity large enough to require only one search resource per target structure and that the search resources have adequate support to operate independently. Additionally, the perturbation parameters considered are independent with respect to the search resources. Therefore, the search resource completion times are independent. Letting \( m \) be the number of search resources, the stochastic robustness metric, \( SRM \), is defined as:

\[
SRM = \prod_{i=1}^{m} P(SRC_T \leq SDT).
\]  

(3)

Thus, for a given resource allocation of search resources to target structures, the \( SRM \) provides the quantitative value for the robustness of the allocation. This can be used to compare the robustness of one proposed allocation versus another; selecting the more robust allocation (the one with the higher \( SRM \), i.e., the higher probability of success).

The framework for a model of search and rescue, and the robustness metric \( SRM \), can be used as the objective function in resource allocation heuristics that derive robust allocations. This is analogous to what we have done in studies such as [18, 16].

The critical, and difficult, research that needs to be done for the post-disaster search and rescue environment is refining this framework model. In particular, one must enumerate the relevant perturbation parameters, build the pdfs, and define exactly \( f_{SC_{ijk}} \).

VI. CONCLUSION

People, animals, and robots will continue to expand their cooperative working relationships on a multitude of difficult tasks. As a result, the PAR Laboratory at Colorado State University is being formed. It has begun its exploration of this rich research field and promises to produce significant work. The cross-disciplinary composition of the laboratory will provide an unmatched opportunity for the development of novel results.

A framework for a model incorporating PAR elements and extension to that model for the search and rescue environment were presented in this paper. The model accounts for uncertainties and produces a quantitative metric that can be used to measure the robustness of a resource allocation. This model can be the foundation for a variety of extensions in this domain. It provides flexibility for the user to define the fitness function and identify the perturbation parameters of interest. This extension demonstrates the potential for PAR research and requires further research to develop it fully. It is an excellent fit for the environment and the problem domain due to its use of stochastic information for modeling what is an extremely uncertain field – post-disaster recovery.

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REFERENCES


