Autonomous Mobile Robots and Distributed Exploratory Missions*

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Abstract. This paper presents our design philosophy for robotic teams involved in distributed exploratory missions, such as military reconnaissance, scientific exploration, and security patrols. It outlines the fundamental requirements of these mission types, finds commonalities among them, analyzes the roles robots can play, and notes research areas requiring greater attention.

Key Words: Robotic exploration, Heterogeneous robot teams

1 Introduction

We define *exploratory missions* as those missions in which the primary goal is to gather information about some structure, environment, region, individual, or group. Some manipulation of the environment to aid in information gathering may occur (such as drilling a core sample) but modification of the environment is not in itself a goal of an exploratory mission. Similarly, exploration may be facilitated by the movement of resources (such as positioning a recharging station in the vicinity of the exploration site) but movement of resources is, likewise, not in itself a goal of an exploratory mission. This definition distinguishes exploratory missions from such missions as manufacturing, construction, transportation, and shipping.

While all exploratory missions cover a significant area relative to the size of the robot – requiring robot mobility to complete – in some missions the environment will be inherently distributed. This may mean that the mission requires sensing at many places simultaneously or that other requirements (such as time or fuel available) do not permit a single robot to effectively cover the points of interest. We term such missions *distributed exploratory missions*. By definition, then, distributed exploratory missions require teams of agents distributed throughout the environment. In most cases these will be teams of robots, although robots could be teamed with non-robotic agents in some cases as well.

* This material is based upon work supported by the Defense Advanced Research Projects Agency, Microsystems Technology Office (Distributed Robotics), ARPA Order No. G155, Program Code No. 8H20, issued by DARPA/CMD under Contract #MDA972-98-C-0008.

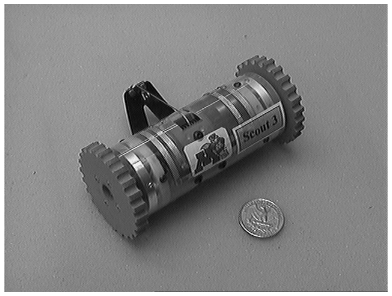

Fig. 1. A scout robot shown next to a quarter for scale

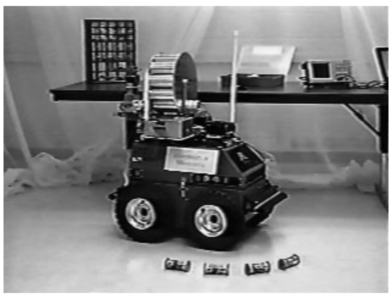

Fig. 2. A team for distributed exploratory missions - a ranger (center) with four scouts (foreground)

We have designed and built a team of robots suitable for a range of distributed exploratory missions. This team is based on a group of small sensor robots we call "scouts" (see Fig. 1) which are detailed elsewhere [1]. The scouts are teamed with larger utility platforms known as "rangers" (see Fig. 2) which provide greater range and computational power to the team [2]. This team can autonomously engage in distributed exploratory missions such as covert surveillance [3].

Others have also built robot teams for exploratory missions, such as aiding in security patrols [4], or to study particular tasks that might be useful in exploratory missions, such as map making [5] or "bounding overwatch" (a team travel method that keeps one group on the lookout while the other group moves) [6].

In the present paper, we take a broader view of distributed exploratory missions to identify fundamental requirements of these mission types, find commonalities among them, analyze the necessary and desirable abilities and characteristics of robots intended for such missions, and note research areas requiring greater attention.

2 Types of distributed exploratory missions

While we do not seek to exhaustively categorize all possible distributed exploratory missions, a selection of common mission types will be useful in our analysis of the shared and distinct elements of various distributed exploratory missions.

Evaluation of accidental releases These are missions to quickly gather information about accidental releases of hazardous materials, such as toxic chemicals or nuclear waste. We envision an exploratory mission as most likely in the event that the release takes place during transport, since releases at production or consumption locations are likely to be monitored by previously emplaced sensors.

Scientific exploration These are missions in which the primary purpose is to collect information of scientific interest. In general, these missions will take place in hard to reach or dangerous environments which preclude human exploration. These include lunar, planetary, volcanic, polar, and deep sea environments.

Traditional tactical military reconnaissance These missions are for gathering information on terrain and enemy positions. Traditional tactical military reconnaissance excludes urban zones as these have been historically avoided.

Urban reconnaissance Urban reconnaissance serves the same purpose as traditional military reconnaissance but provides additional challenges. The close quarters of urban settings put troops at great risk and urban building materials can hamper radio communications. Also, the immediacy of the enemy means that reconnaissance may need to be done under fire. Finally, urban reconnaissance may be useful for law enforcement groups, such as Special Weapons And Tactics (SWAT) teams, as well as the military.

Surveying Surveying is preparatory to map making. The maps created are highly accurate with regard to the distances and angles recorded during the surveying missions and, therefore, differ from most of the maps made in other mobile robotics missions.

Security patrol Security patrols are surveillance missions in which the objective is to keep an area (such as a home, office, factory, or military encampment) safe. Unlike the use of emplaced security devices (such as burglar alarms or smoke detectors), security patrols involve moving throughout the area to be protected.

Survivor detection and location Disasters, such as earthquakes, explosions, or chemical spills can leave survivors in places that are difficult or dangerous to traverse. Finding survivors quickly and determining their locations to bring help is paramount in saving lives.

2.1 Mission facets

From the mission type descriptions above, we can see distinct facets of the various missions. These include:

- the necessity for covert operation,
- an expectation of opposition,
- a requirement for special deployment methods,

- the possibility that the environment is hazardous to people,
- the difficulty that the environment is not controlled, and
- the fact that the environment is not known in advance.

These facets are presented in such a way that having one or more of them is likely to make the mission more difficult to complete.

The necessity for covert operation means that the mission may be compromised if one or all of the robots is observed by individual(s) not part of the mission group. For example, a security patrol may fail to detect an intruder if the intruder sees the patrol coming and is able to hide away until the patrol has passed.

Opposition means that there are agents actively trying to thwart the mission, perhaps by impeding travel, blocking communications, or even damaging or destroying the robots. These enemies may, however, only seek to evade detection or otherwise provide inaccurate information, as more aggressive actions may be too informative for the robots (e.g., by revealing enemy positions). Evasion will often be the favored mode of opposition in security missions.

While all robots need to be deployed into their mission areas, for some missions it will be enough to have the robots carried into position and deployed by standard means (e.g., transportation by trucks, vans, or other standard vehicles; unloaded by human operators) but for other missions special deployment will be necessary. Special deployment includes being launched from rockets, dropped from aircraft, and released underwater. Special deployment can also refer to the deployment of only some members of a robotic team, such as when a larger robot deploys sensor robots.

If an environment is hazardous to people, then the robots will either not be able to work closely with people or the people must be specially equipped to enter the environment. In either case, the need for robot autonomy is increased. (While the expectation of opposition could be thought of as providing one case of a hazardous environment, we will restrict our definition of a hazardous environment to exclude active opposition and keep these notions separate.)

If the environment is controlled, it can be modified or adapted to the robots. A security patrol in a factory, for example, can be supported by providing landmarks or wireless communication nodes where needed. If the environment is not under the control of the mission team, such modifications are not possible.

Finally, if the environment is largely known, plans can be made ahead of time and/or with a global view in mind. Otherwise, the robot must discover the large features of its environment as it explores.

2.2 Mission types vs. mission facets

The mission types discussed above (Sect. 2) share many similarities yet have many differences as well. Their similarities and differences with respect to

Table 1. Mission Types vs. Mission Facets

	Covert Operation	Opposition Expected	Deployment Issues	Hazardous Environment	Uncontrolled Environment	Unknown Environment
Accidental Releases	N	N	Y	Y	Y	?
Scientific Exploration	N	N	Y	Y	Y	Y
Trad. Reconnaissance	?	Y	Y	?	Y	N
Urban Reconnaissance	?	Y	Y	?	Y	?
Surveying	N	N	N	?	Y	N
Security Patrol	?	Y	N	?	N	N
Survivor Detection	N	N	Y	Y	Y	?

the mission facets of Sect. 2.1 are summarized in Table 1. In the table, 'Y' indicates the mission has this facet, 'N' that it does not, and '?' that it may vary and is, therefore, discussed below. Because these facets add difficulty to a mission, more 'Y' entries in the row for a mission type indicate more challenges that need to be overcome.

Evaluation of accidental releases has only one '?' symbol in the table. These missions may vary as to whether a map is available, in which case the environment is known. While it is unlikely that a map designed specifically for robotic use would be available for such a mission, maps intended for human use are likely to be available. For this and other robotic exploratory missions, it would be worthwhile to develop appropriate technology to allow robots to use maps made for people.

Traditional military reconnaissance may be carried out covertly although it is not necessary to mission success in all cases. It may also take place in areas that have been contaminated (for example, by chemical or biological weapons), if robots are used rather than human troops.

Like traditional military reconnaissance, urban reconnaissance may be done covertly in some cases. However, in cases where urban reconnaissance is done under fire, covert operations are not possible. Also as with traditional military reconnaissance, urban reconnaissance may take place in areas contaminated by hazardous materials when chemical or biological weapons are in use. Unlike traditional military reconnaissance, however, urban reconnaissance is likely to take place in areas where the basic layout of the physical features is unknown.

Surveying is not normally done in hazardous environments. However, this may change if robots are the only ones at risk during such missions.

Like military reconnaissance, security patrols may be carried out covertly. However, they may also be done openly to discourage illegal activity. Robotic security patrols may occur in places that pose intrinsic hazards to human health or that may become hazardous in some circumstances (e.g., when toxic fumes are released by burning materials).

As with evaluation of accidental releases, a map designed for robotic use in the detection and location of disaster survivors is unlikely to be available, although maps intended for human use are likely to be available. However, in disaster situations previous knowledge about the area may not prove useful after the disaster strikes since earthquakes, floods, etc. may radically alter the physical layout of the environment.

3 Robot abilities and characteristics

Because distributed exploratory missions require multiple agents, we will generally consider teams of robots rather than single robots. However, it is important to consider robot abilities and characteristics individually as well as collectively. We can then match these individual and team abilities and characteristics with distributed exploratory missions types.

Robot abilities or characteristics needed or useful for distributed exploratory missions include:

- movement,
- sensing,
- reporting,
- information evaluation,
- localization,
- navigation,
- map following,
- map making,
- heterogeneity of the robots,
- the ability to team with non-robotic agents.
- special deployment methods,
- group movement methods,
- planning,
- coordination,
- the ability to communicate throughout an area.

To complete any distributed exploratory mission, the robots must be able to move, sense, and report back. Naturally, the movement and sensing modalities must be appropriate for the particular mission(s) undertaken. Reporting of collected information may be piecemeal to ensure that information is received as soon as possible and to prevent total mission failure should disaster occur. Alternately, collected information may be stored for later analysis in cases where transmission is impossible or undesirable (such as covert missions where radio silence must be maintained).

The information collected may be needed by the robots to complete the mission itself, in which case it needs to be evaluated by the robots in real time – that is, *perceived* – or may be useful for later evaluation by people or more powerful computers. In the missions we envision, at least some of the information will need to be used for perception (for example, to visually guide a robot to a location) while other information will be used elsewhere and/or for less immediate purposes.

Localization is important to all exploratory missions but the type of localization can vary. The robot may need to know its coordinates relative to the world or structures in it, may need to know its coordinates relative to one or more other robots in the group, may not need to know its own coordinates as long as others do, or even may not need to know its own coordinates at all as long as others can find it (e.g., by activating a homing beacon once a survivor has been found in a rescue mission).

Navigation, interpreted broadly to mean intentional movement from place to place, is likewise important to all exploratory missions. This may include random walks executed for area coverage but in most cases will be more directed. Navigation may be based on information including landmarks, sensor gradients, and maps.

Map following, then, can be seen as a special case of navigation. Maps may be topographical or may be more abstract and relational. Not all exploratory missions will involve map following.

Some exploratory missions may involve map making. Whether map making is a part of a given mission will depend on such factors as whether a map is already available, whether a map is necessary to complete the mission itself, and whether constructing a map is a goal of the mission. In some cases, such as locating earthquake survivors in rubble, the environment may be too complex or confused to allow for mapping.

Heterogeneity is a characteristic of teams or groups. The creation of heterogeneous robot teams involves the production of robots that are specialists, either in terms of their hardware or their roles within the team, rather than generalists.

Similarly, specialization may be brought in by taking heterogeneity one level higher and teaming the robots with non-robotics agents, such as people or dogs.

As mentioned in Sect. 2.1, some exploratory missions may require special deployment methods. Likewise, special group movement methods, such as platooning, may increase team effectiveness. Planning and coordination may be needed in many missions, although in some cases totally reactive behaviors may be sufficient. Finally, the ability of robots to act as communication relays can keep a team intact over larger areas or where the environment severely limits radio range.

Table 2. Mission Types vs. Robot Characteristics.

	Map Making	Map Following	Heterogeneity of Robots	Teaming with Non-Robots	Group Movement	Planning	Coordination	Communication Relays
Accidental Releases	?	Y	Y	N	Y	Y	Y	Y
Scientific Exploration	Y	Y	Y	N	Y	Y	Y	Y
Trad. Reconnaissance	N	Y	Y	?	Y	Y	Y	Y
Urban Reconnaissance	?	?	Y	Y	Y	?	Y	Y
Surveying	Y	Y	?	?	?	Y	Y	Y
Security Patrol	N	Y	Y	?	Y	Y	Y	?
Survivor Detection	?	?	Y	Y	Y	Y	Y	Y

3.1 Mission types vs. robot characteristics

As mentioned in Sect. 3, all missions require the robots to be able to move, sense, report, evaluate at least some of the information sensed, localize, and navigate. Table 2 summarizes whether other abilities or characteristics are important for each mission type. In this table, 'Y' indicates the mission requires robots or teams to have this ability or characteristic, 'N' that it does not, and '?' that it may vary and is, therefore, discussed below.

While making a map is generally more difficult than not making one, map following may actually be easier than other forms of navigation. Producing specialized robots may be easier than producing robots that can perform all required tasks, but heterogeneity generally means more planning and coordination is needed to get the proper robot to the proper place. Teaming with non-robots means that some specializations or abilities do not need to be embodied in robot agents but adds difficulties in terms of interactions and shared information. Group movements can simplify some logistics and increase efficiency but may require hardware or software adaptations to allow it. A need for planning and coordination adds difficulty, as does the requirement that some or all of the robots be able to act as communication relays.

With evaluation of accidental releases, map making is not an intrinsic part of the mission but may be required if a map is not available to follow. It may be noted that this mission type would then require both map making and map following. This is not as contradictory as it might first appear as it is possible to follow partial maps to frontiers of unexplored space and incrementally build larger maps [7]. The build-and-follow strategy would be present in scientific exploration and possibly urban reconnaissance missions as well. For traditional military reconnaissance, the basic layout of the environment is known and overall maps do not need to be made. However, reconnaissance allows changes to be noted and details to be added to the existing map. This is also true of most surveying missions.

Traditional military reconnaissance could be done by robots alone but could also be done by mixed human/robot teams. In urban reconnaissance, on the other hand, people will always be present, often including bystanders. Also unlike traditional reconnaissance missions, urban reconnaissance will often proceed without a map.

Surveying by definition involves map making and following. Surveying also requires planning and coordination but the survey team composition and movement types can vary.

As mentioned previously, in disaster situations the state of the environment will determine if it is possible to make or even follow an available map.

4 Overall similarities

Two mission facets are common to many of the mission types we have discussed. These are:

- a need for special deployment methods (true in five of seven mission types), and
- the fact that the environment is not controlled and therefore not subject to prior adaptations on behalf of the robots (true in six mission types).

Additionally, a hazardous environment is a likelihood in three mission types and a possibility in the rest.

Similarly, some abilities and characteristics of robots or robotic teams were found to be common in the mission types we have examined. These are:

- map following (needed in five mission types and possibly needed in two others),
- heterogeneity of the robots in a team (definitely valuable in six mission types and potentially valuable in the seventh),
- specialized group movements (definitely useful in six mission types and potentially so in the seventh),
- planning (needed in six missions types and possibly needed in the seventh),
- coordination (needed in all seven missions types), and
- communication relay ability (needed in six missions types and possibly needed in the seventh).

These commonalities – together with the universals of movement, sensing, reporting, perception, localization, and navigation – should not only be seen as areas in which individual research should be pursued but should be taken together when designing robotic teams intended for exploratory missions.

5 Conclusions

We have given an overview of exploratory missions, examining inherent facets of the missions and the abilities and characteristics needed by robots and robotic teams in order to accomplish these missions. We have found many similarities in both mission facets and robotic requirements across the mission types we have considered, and have drawn attention to them.

While we have considered only those missions in which exploration and transmission of gathered information are goals, exploration may be a part of a larger mission, such as search and retrieval [8]. In these cases a distributed, heterogeneous robotic team may also prove quite useful. By distributing numerous, remote, mobile, sensor robots throughout the area to be searched, the objects to be retrieved can be located quickly. If speed is a high priority, then it will not do to have a few, large retrieval robots spending their time searching when they could be kept busy transporting items, if only they knew where the items were. The relatively small cost of scouting robots is more than repaid by the greater coverage area of all their sensors put together.

References

1. D. F. Hougen, S. Benjaafar, J. C. Bonney, J. R. Budenske, M. Dvorak, M. Gini, D. G. Krantz, P. Y. Li, F. Malver, B. Nelson, N. Papanikolopoulos, P. E. Rybski, S. A. Stoeter, R. Voyles, and K. B. Yesin. A miniature robotic system for reconnaissance and surveillance. In *Proc. of the IEEE Int'l Conference on Robotics and Automation*, San Francisco, CA, April 2000. To appear.
2. D. F. Hougen, J. C. Bonney, J. R. Budenske, M. Dvorak, M. Gini, D. G. Krantz, F. Malver, B. Nelson, N. Papanikolopoulos, P. E. Rybski, S. A. Stoeter, R. Voyles, and K. B. Yesin. Reconfigurable robots for distributed robotics. In *Government Microcircuit Applications Conference*, Anaheim, CA, March 2000. To appear.
3. P. E. Rybski, S. A. Stoeter, M. D. Erickson, M. Gini, D. F. Hougen, and N. Papanikolopoulos. A team of robotic agents for surveillance. In *Proc. of the Int'l Conf. on Autonomous Agents*, June 2000. To appear.
4. H. R. Everett and D. W. Gage. From laboratory to warehouse: Security robots meet the real world. *Int'l J. of Robotics Research*, 18(7):760–768, July 1999.
5. W. Burgard, D. Fox, M. Moors, R. Simmons, and S. Thrun. Collaborative multi-robot exploration. In *Proc. of the IEEE Int'l Conference on Robotics and Automation*, 2000. To appear.
6. L. Parker. Multi-robot team design for real-world applications. In H. Asama, T. Fukuda, T. Arai, and I. Endo, editors, *Distributed Autonomous Robotic Systems 2*, pages 91–102. Springer-Verlag, Tokyo, 1996.
7. B. Yamauchi. A frontier-based approach for autonomous exploration. In *Proc. IEEE Int'l Symposium on Computational Intelligence in Robotics and Automation*, pages 146–151, Monterey, CA, July 1997.
8. P. E. Rybski, A. Larson, M. Lindahl, and M. Gini. Performance evaluation of multiple robots in a search and retrieval task. In *Workshop on Artificial Intelligence and Manufacturing*, pages 153–160, Albuquerque, NM, August 1998.