Heterogeneous Collaborative Swarms of Autonomous Agents with Varying Capabilities

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ABSTRACT

The overall purpose of this paper is to develop a heterogeneous collaborative swarm of entities with varying capabilities operating within different levels of information clouds where knowledge is shared either between vehicles, between vehicles and base stations, or between different clouds. The entities, or agents, may be of robot form (ground, air or sea vehicles) or human form and will have different specializations for knowledge gathering and sharing. Agents will combine to make a single group or collection of groups to form the entire Swarm as they work individually or collectively to accomplish various goals. The Swarm will consist of two levels of information clouds, one global and many local, that allow information to be collected and shared. The local cloud may be a collective cloud, where all information is stored via a single entity such as a base station while individual agents may communicate with each other, or the cloud may be disjointed where information is only sent and the relevant knowledge is received by individual agents The local clouds will all be connected via a single global cloud where information is sent to a central database and operations center. At the global cloud level, information is used to decide on mission objectives or is passed to other clouds to be used. Research will focus on the different aspects of the two cloud types, how knowledge is shared and used, and how each agent reacts to the information given mission parameters.

Keywords

Swarm Intelligence, Heterogeneous Swarm, Sensor Fusion, Centralized and Decentralized Control

1. INTRODUCTION

It seems today there is always a new article or report on robotics. Whether it is academia, the military, or just for fun, many people seem to be excited about the potential of robots that can perform jobs and tasks on their own. Many of these same groups are not just interested in how robots may work autonomously, but how they may work together. Interest has gathered about robots that cooperatively work together, while various other groups focus on a more biologically inspired idea such as swarm cooperation.

There are many different ways to define cooperative and swarm robotic systems. In some definitions, a cooperative system revolves around a set of autonomous agent, sometimes at little as two, which will occasionally rely on and work with each other to accomplish a task. An agent within a cooperative system is typically capable of handling a set of tasks alone; however, they often share world knowledge and arbitrate on how specific tasks should be completed. One such group is focusing on hierarchical network control for cooperative robotics with military application [1]. A swarm system is typically made of a large group of robots, a minimum of three, which work closer together at accomplishing a specified task than a cooperative system. Swarms typically share knowledge as a group memory, are very robust, and handle most tasks together; however, they are themselves usually not very capable vehicles. Most swarms cannot accomplish very difficult tasks and rely heavily on communication abilities between vehicles in the swarm [2].

Though there have been various levels of research on cooperative or swarm systems, it has mostly been held to specific control or sensor fusion schemes. Some cooperative systems focus on how behaviors are chosen between vehicles depending on the world model. Various swarm systems follow some of the same patterns, but focus heavily on how information is stored and shared or emergence. More so, it is very rare to see either of these systems that focus on how vehicles of different areas (ground, air, sea) will work together to accomplish either a swarm or cooperative system.

The goal of our research is to develop a heterogeneous collaborative swarm of entities working with different levels of information clouds in a real environment. This paper discusses the cloud structure while explaining the different types of agents that will exist within the system. Communication schemes between systems within the cloud will be detailed in terms of a centralized and disjointed scheme. Finally, a few of the expected system outcomes will be detailed.

2. Cloud Structure

As described, the cloud structure will be made of a single global cloud and many local clouds. The purpose of the various clouds is to be communication pathways between agents, cloud levels, and end users. Knowledge sharing within local clouds depends on which cloud structure is used (centralized versus disjointed). Knowledge is gathered by multiple local clouds and is then passed to the global cloud, which is contained within the Internet. The global cloud will describe the state of the world knowledge for all clouds as well as current mission objectives and progress. Knowledge from the global cloud may be reproduced in a single Operations Center where it is viewed by end users, processed, and mission objects are modified as needed. Knowledge from the global cloud may also be passed to other local clouds within the Swarm.

Though information is typically simply sent and received between clouds and mission parameters are sent down from the global cloud, certain agents (human) are able to modify mission parameters if they are part of a given cloud. While implementation of the cloud is not specific, the current cloud structure and communication is performed within the Google Cloud using Google App Engine.

One focus for both the centralized and disjointed cloud structure will also be handling the ability for all agents to communicate with the cloud. Occasionally an agent may leave the communication range of the base station for the cloud. In this situation, a mixed form of bridging (or repeating) communication will be used between multiple vehicles to pass information from the external agent through agents within the communication range of the base station.

2.1 Centralized Local Cloud

The centralized local cloud structure resembles more closely to a Swarm behavior structure. The overall structure focuses on intercommunication within a single cloud between agents of that cloud acting as a squad and a central base station acting as a squad leader. The base station may be a more specialized and capable agent or simply a computer station. In implementation, the base station will hold multiple forms of communication (Wi-Fi, RF, 3G/4G modem, etc.) on a single tower as well as a high-speed computer at the base. The cloud is further made up of multiple agents with their own specializations. Knowledge gathered by the individual agents is directly shared with the base stations and may be indirectly shared with other agents within the cloud. Local level tasks may be decided upon by the base station given parameters of the mission and world knowledge. These tasks can then be directed at specific agents or groups of agents to complete said task. Task goals and progress are shared as knowledge.

2.2 Disjointed Local Cloud

The disjointed local cloud structure resembles a mixed topology of Swarm and Cooperative/Distributive behaviors. The cloud is made up of virtual connections between agents with no central agent processing the knowledge. A central tower is still in place for communication; however, this tower mainly represents the connection of the virtual cloud to the global cloud. Knowledge is broadcasted from each agent within the cloud. All knowledge is directly gathered into the global cloud, while only relevant knowledge is retained for agents given their own specializations. Given that no central base station is used to decide on local level tasks, each agent must be capable of arbitrating new tasks given the collected knowledge and mission parameters. A cost function and consensus/voting scheme may be used between agents to decide how tasks are completed.

3. Swarm Agents

The Swarm consists of robotic agents (ground, air or sea) or human agents. Each agent has its own purpose and specializations within their given clouds. Agents are formed

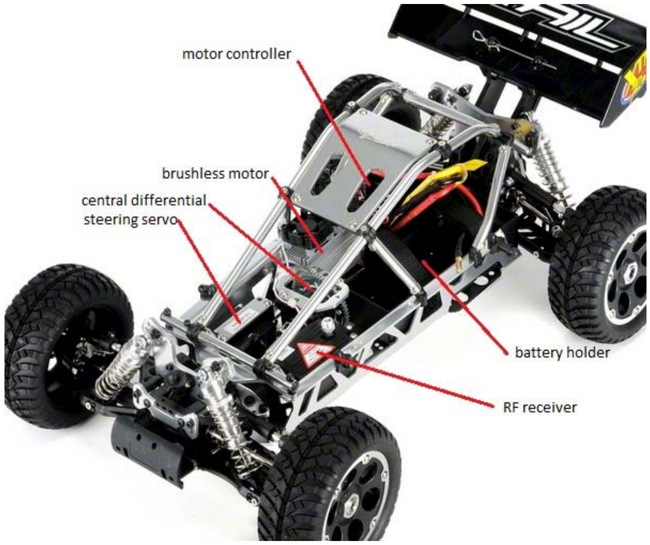

Figure 1. The XTM Rail

within local clouds as needed and desired by mission parameters and tasks given by the global cloud.

3.1 Robotic Agents

Each robotic agent will hold its own level of control and survival behaviors, only receiving any type of directional commands via trajectories or GPS waypoints from the local cloud. Robotic agents have specific abilities that allow them to accomplish certain tasks, e.g., sonar and GPS for basic object detection [4], cameras for computer vision, etc. Robotic agents have communication abilities to send and receive data directly to local clouds via Wi-Fi or RF, while only using 3G/4G in special circumstances. Commands or mission object updates will be sent to robotic agents only from base stations, while intercommunication of knowledge may be shared between other robotic agents or base stations. At times, if an agent moves out of range of a base station, communications may be established with agents that are within range to pass information to the base station. At times, human agents through the cloud may indirectly control robotic agents.

An example of one such agent used within this system as a robotic agent is the XTM Rail 1/8 scale buggy (as seen in Figure 1). This vehicle was used in previous research focused on single vehicle swarms with emergence [3] and a recent paper focused on developing those swarms with more behaviors [4].

3.2 Human Agents

Human agents share multiple purposes in the cloud swarm. In most situations, human agents have the ability to directly affect the mission objects for various clouds. Information from the global cloud is sent directly or indirectly (through base stations) to human agents. With this information, human agents may change mission objects or directly move agents to areas of interest, therefore overriding or removing them from the current mission object for a limited time. Human agents may also share information with the cloud, either through special abilities (sensors, GPS, etc.) located on the human agent or through knowledge updates/commands sent from the human agent.

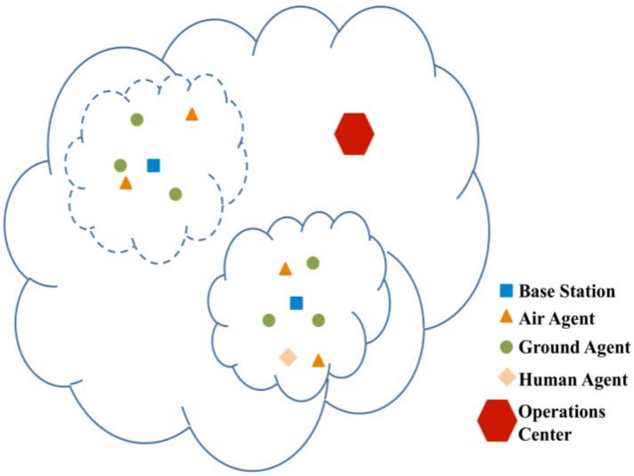

Figure 3. A Description of the complete cloud structure. The solid cloud represents the centralized local cloud, while the broken cloud represents the disjointed cloud. All clouds and components are contained within a larger global cloud.

4. Swarm Communication and Control Application

The overall structure of the cloud and the related components is shown in Figure 3. The method and pathways, as given in sample form (see Figure 2), for communication and control is described below.

4.1 Pathways within a Centralized Cloud

Data passes in multiple directions when dealing with the various clouds. At the low level, agents travel throughout their environment gathering knowledge and performing tasks given their specializations. Knowledge takes the form as objects or points of interest found in the environment, or as task updates. In a centralized cloud, as knowledge is gathered, that information is shared directly with a base station and indirectly with other agents. Knowledge is then passed from the base station of the local cloud to the global cloud within the Internet. From here, information may either be passed to other local clouds if needed, or to a central Operations Center. Knowledge at the Operations Center is used for end users to view the Swarm world knowledge. Either the computers in the Operations Center or the end users may modify mission parameters if desired. From the Operations Center, via the global cloud, mission parameters are sent to each local cloud. Given world knowledge of the local cloud and any other relevant local cloud, as well as mission parameters, a base station will arbitrate and decide tasks for individual or groups of agents.

Human agents may be contained within a local cloud and behave slightly different than robotic agents. Knowledge is gathered by a human agent either indirectly (sensors, GPS, etc.) or directly (information entered into cloud). This information follows the same pathways as robotic agents, except in terms of direct commands given by a human agent. While in a cloud, a human agent can redirect or change a mission parameter for an individual or group of robotic agents. When finished, a human agent can then release said robotic agents back to the control of the base stations.

4.2 Pathways within a Disjointed Cloud

At the low level, information travels differently in a disjointed cloud versus the centralized cloud. As agents travel throughout the environment gathering knowledge, the knowledge is broadcast between all vehicles. Knowledge is either collected by the global cloud or by agents who may use the knowledge given their specializations. Once in the global cloud, the knowledge is treated the same as was in the centralized cloud, resulting in mission commands or modifications being sent to local clouds. When a mission command is received within the disjointed virtual local cloud, each agent received the updated mission command. Using the gathered world knowledge, current mission objectives, and any updated mission objectives from the global cloud, all local agents will adjudicate on all information and come to a consensus on individual or groups of agents needed to complete a task.

In the disjointed cloud, the human agent behaves the same way as in the centralized cloud.

5. Research Focuses

Various research focuses will be followed during the development and work on the previously described system. Each is described below in detail as to what areas are currently being reviewed.

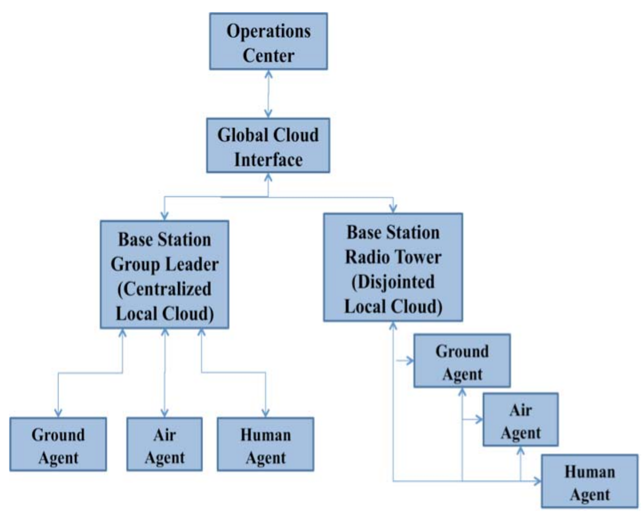

Figure 2. A sample Hierarchical design of information packets passed between local clouds, global clouds, and operations center.

5.1 Swarm Environment Map Building

With a heterogeneous group of robots with different sensing capabilities, the principal goal would be to use all the sensor data to compile a model of the environment around the cloud. We could start with a priori knowledge of the lay of the land (from a map with GPS coordinates or an overhead image) and start filling in the details as the agents explore and sense their surroundings and update the local cloud.

Based on the data available, the local cloud could then decide upon points of interest to investigate. This could be done by the base station in case of a centralized cloud or by each individual agent in a distributed cloud. Points of interest could also be identified by the Operations Center and pushed down through the Global cloud. The local cloud would then have to decide on a configuration that would cover all these points and come up with trajectories to transition to those configurations.

5.2 Cloud Based Trajectory Planning

Trajectory planning approaches would be different for different cloud structures. The challenges faced here would be developing efficient trajectories for non-holonomic robots in an unstructured environment with hidden/unknown obstacles [5]. For a centralized cloud, the base station would use the overall desired configuration to develop trajectories for each agent and pass them on to each agent as waypoints. For a distributed cloud, each individual agent would have to generate trajectories relative to the other agents, which would result in the cloud reaching the desired configuration.

Trajectory planning could be done using optimal observer based models or heuristic based approaches. Based on constraints for each mission, different techniques could be exploited. For example, in the centralized control scheme, and exhaustive optimal observer based model could work if the base station has enough processing power to tackle the problem. However, in the distributed approach, a less computationally expensive, heuristic based approach could be called for with cost functions based on coverage and time, tailored to help the decision making process. Trajectories could even be developed and pushed down from the global cloud.

5.3 Cloud Transitioning

The agents should also be capable to transition from centralized cloud to disjointed cloud and back. Should the base station drop out, the agents should still be able to complete the mission at hand, working as a disjointed could. If the base station were to come back up, the disjointed cloud should be able to utilize its superior processing power and transition back to a centrally controlled cloud.

5.4 Centralized versus Decentralized Control

For a centralized cloud, the base station is aware of the agents and the desired goal. Hence it makes sense to have an orchestration algorithm running on the base station or the cloud, which computes trajectories for each agent and the agents track these trajectories. Various orchestration algorithms could focus on different cost functions, like maximizing coverage while minimizing time or optimizing effort.

The problem with centralized controllers is that the base station or the cloud has to be in constant communication with the agents. That would limit the effectiveness of the swarm. Hence a decentralized control approach would be much more effective in regions where the robots would have to move in and out of communication with the rest of the swarm but be in constant contact with the nearest neighbor [5]. However, if there is a constant chatter of control signals, the swarm would lose bandwidth required for sensor data. Hence the best control algorithms would maintain connectivity without having to exchange control signals between robots.

5.5 Multiple Levels of Arbitration

When a mission gets authorized from the global cloud, the local cloud would have to break it down into individual tasks for each robotic agent. For example, an air vehicle could be tasked to scout out the area of interest to locate possible targets which would then be passed on to the ground vehicles. If the local cloud were a centralized cloud, the base station would be in charge of distributing the mission tasks amongst the various robots in the cloud. The base station would also monitor and collect data from various members in the local cloud and pass it on to the global cloud.

To handle orchestration at the local cloud level, the base station would need to have better computational capabilities than the other robots in the swarm. If the orchestration layer were deployed on the global cloud, then the base station would receive individual mission parameters for each robot. It would have to collect state information from each robot and relay data to the global cloud. Such a system would not require the base station to have more computational resources compared to the other robots.

However in a distributed local cloud, the mission parameters would be received by all the robots in the cloud. Based on their capabilities and the position of the targets, each robot would generate an expected completion metric of all the tasks in the mission. The robots would broadcast these metrics on to the local cloud. The swarm would then reach a consensus based on these metrics and the tasks in the mission would be assigned to the appropriate robot. The task assignments would then be relayed to the global cloud which could monitor progress and completion.

5.6 Sensor Fusion with Heterogeneous Agents

Sensor data from different robots in a heterogeneous group with different sensing capabilities could be used to build a better position and orientation estimate for each robot in the group [6]. The estimation algorithm could be centralized or decentralized. Also with different heterogeneous robots, different perspectives of the environment can be used to anticipate obstacles and determine paths of least effort while maximizing coverage.

6. Demos

Various demos are planned for 2013 that demo the abilities of the collaborative swarm and cloud. Search and Rescue will demo how air vehicles will be used to perform reconnaissance and place the information on the cloud while various ground vehicles will collect the gathered information and identify any targets of interest. Urban Exploration will show how both the air and ground vehicles work together to explore an enclosed area with tall buildings and multiple hidden corners for a human agent to transverse. Perimeter Maintenance will show how air and ground vehicles may be used to protect a specified mobile perimeter with a high level of coverage given the various levels and types of vehicles.

Vehicles will operate in the Ubuntu environment with the cloud existing within the Google App Engine. A human agent can either view or control various aspects of the cloud via an Android Tablet that gives status updates and control to the user. This information is passed from the tablet into the cloud for processing. An operations center will also be used to start and modify missions.

7. Conclusion

In this paper we described a heterogeneous collaborative swarm of entities that operate within a real environment with different levels of information clouds. We went into detail of how the various levels of the cloud structure work together as well as how the various types of agents within the swarm communicate and work. We described the various communication schemes between agents and the clouds in terms of the centralized and disjointed schemes. Finally, various levels of research that are or will be performed within this research focus were detailed.

8. ACKNOWLEDGMENTS

9. REFERENCES

[1] "Towards command and control networking of cooperative autonomous robotics for military applications (CARMA)"; Jacoby, G.A.; Chang, D.J.; Electrical and Computer Engineering, 2008. CCECE 2008. Canadian Conference on , vol., no., pp.000815-000820, 4-7 May 2008

[2] "An extensive review of research in swarm robotics"; Mohan, Y.; Ponnambalam, S.G.;Nature & Biologically Inspired Computing, 2009. NaBIC 2009. World Congress on , vol., no., pp.140-145, 9-11 Dec. 2009

[3] Emergent Collective Behavior in Autonomous Synergistic Swarm Robots; Sean Wright, Dr. A. Antonio Arroyo, Ian A. Arroyo, Joseph W. Simpkins, Brock Wright, Dr. Lavi M. Zamstein - Florida Conference on Recent Advances in Robotics, Gainesville, FL, 4-5 May 2011

[4] Orchestration of Intelligent Ground Vehicles into a Homogeneous Swarm via the Google Cloud; Gautam Dash, Joshua Weaver, Dr. A. Antonio Arroyo, Sean Wright, Dr, Eric M. Schwartz - Florida Conference on Recent Advances in Robotics, Boca Raton, FL, 10-11 May 2012

[5] Ensuring Network Connectivity for Nonholonomic Robots During Rendezvous; Z. Kan, A. P. Dani, J. M. Shea, and W. E. Dixon - IEEE Conference on Decision and Control and European Control Conference (CDC-ECC), Orlando, FL, December 12-15, 2011

[6] Distributed multirobot localization; Roumeliotis, S.I. - Robotics and Automation, IEEE Transactions on , vol.18, no.5, pp. 781- 795, Oct 2002