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# A Brief Survey and Analysis of Multi-robot Communication and Coordination

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*Abstract*—**Robot navigation is one of the basic problem in robotics. In the field of multi robot systems, it has become an interesting area for researchers to design algorithms that co-ordinate the movement and control the communication of multiple robots. A big challenge in this area is to design a suitable framework which makes multiple robots to work as a team to perform their task and reach their goal. In this paper, we present a brief survey of various researches being carried out in the field of multi-robot coordination and communication. We also present a framework for multi robot coordination and communication with the help of cloud. In this framework, Particle Swarm Optimization (PSO) has been used for coordination whereas Cluster Head Gateway Switch Routing (CGSR) protocol is used for communication among the robots.**

*Index Terms*—**Multi-robot communication; Multi-robot coordination; Cloud Computing; coordination and communication; swarm robotics; PSO; Cloud Robotics**

## I. Introduction

Social insect societies are distributed systems in which colony level behaviour emerges out of interactions among individuals. Designing multiple simple robot systems is better and cheaper than installing a single complex robot in many applications. Moreover it provides a great degree of fault tolerance. Hence significant amount of research has been done in the field of robotic swarm. The robot's behaviour can inspired by natural flocking of birds, ducks,ants etc. The remarkable progress of mobile robotics has attracted a number of researchers in this field. Coordination among the robots may be of two types, centralized and decentralized. In the centralized approach, a single robot acts as the coordinator which monitors the movement of robots and hence the goal accomplishment is centered round the coordinator. In the decentralized strategy, there is no single coordinator in the environment. Each robot coordinates its own movement and ensures that it does not collide with any other robot while goal accomplishment. Some of the well researched themes in this field of multiple robot coordination include path planning [1], traffic control [2], formation generation [3] and target tracking [4]. When a task requires cooperation, some form of communication must be developed. Since the inception of distributed robotics, communication among multiple robots has been extensively studied. A number of benefits can be incurred from different techniques of communication [5] [6]. Explicit communication is a form of communication in which robots directly interact with each other via message passing. Aggregation is another important task that needs to be performed in swarm robotics to perform a task. The networking solutions must focus on security, interaction and communication. For communication, it is assumed that all robots have a single IP address and that they are connected via Bluetooth, WiFi or 3G.

Our work initiates with providing an analysis of previous work. In section 2, we give a brief overview of important communication algorithms. In section 3, the approaches suggested by various authors for robot coordination have been underlined. Also we have mentioned some of the works in the related fields which have been implemented on cloud. Section 4 describes the proposed architecture for multi-robots communication and coordination in cloud. Finally in Section 5, we have concluded our work underlining the future challenges in this field of our regard.

## II. Multi-Robot communication

Several approaches for communication have been developed for ad hoc mobile networks to deal with the limitations associated with them, such as high power consumption, high error rates and low bandwidth. Defense Advanced Research Projects Agency (DARPA) [7] initiated the research on the use of packet switched, store and forward, radio communication to provide reliable computer communication. Packet radio networking (PRNET) [8] provides the exchange of data between computers that are geographically separated via a common radio channel. An algorithm was designed to organize, control, maintain and move traffic through the packet radio network. PRNET provides highly reliable network transport and datagram service by determining routes dynamically and controlling congestion. Perkins et al. [9] developed a table-driven algorithm 'Destination sequenced distance vector routing' (DSDV), which models mobile nodes as routers. Each mobile node maintains its own routing table and these table updates are periodically transmitted throughout the network. Each entry in the table is assigned a sequence number which enables nodes to differentiate between old and new routes and thereby avoiding loops. In order to reduce the number of loops while routing, Wireless Routing Protocol (WRP) was introduced [10]. Each node in the network maintains a distance table, a routing table, a link-cost table and a message retransmission list. Nodes use update messages to exchange routing tables with

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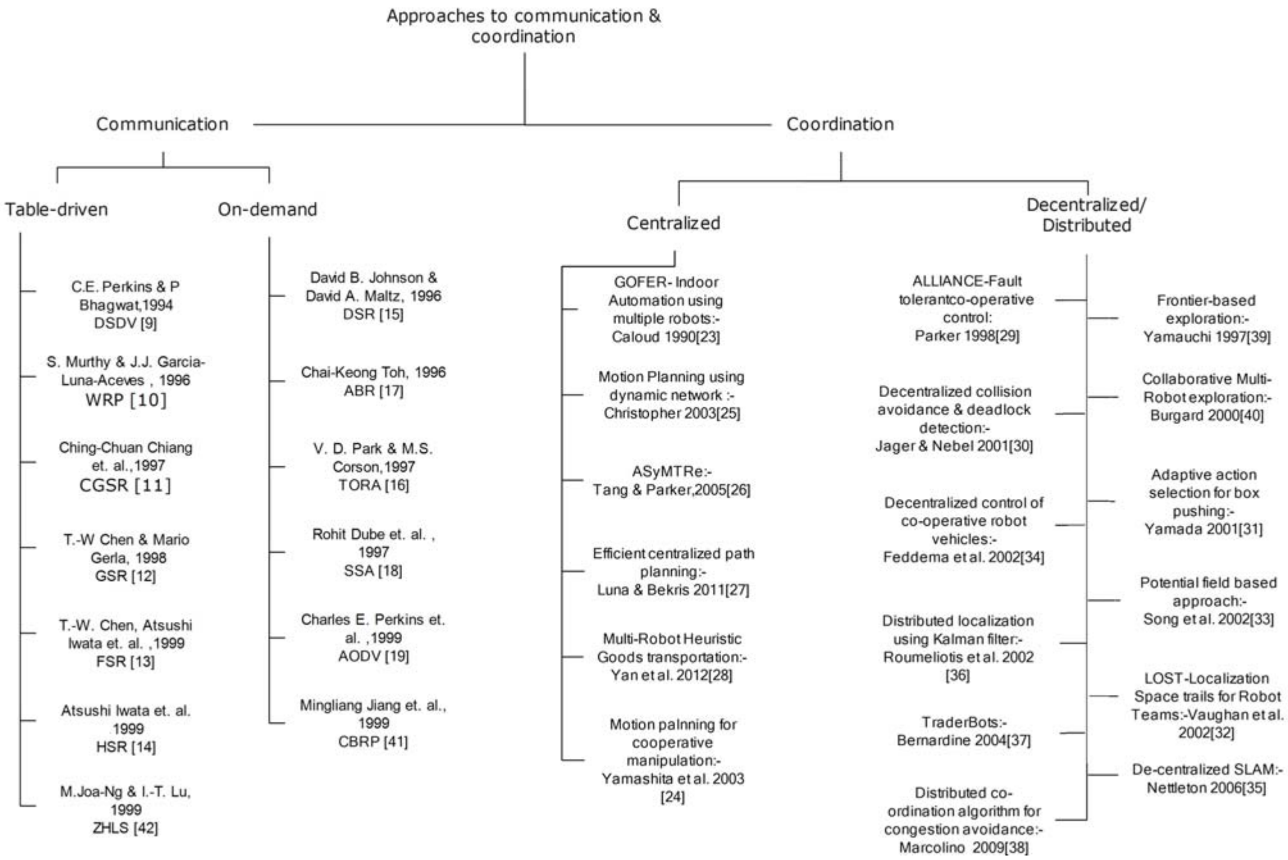


Fig. 1. Survey of the works done on robot communication and coordination

their neighbors. These messages contain list of updates and response list which helps to acknowledge the reception of update messages. It aimed at fast convergence. To overcome the drawback of traditional routing algorithms in dynamic topology, Chiang [11] proposed a heuristic routing scheme Cluster head Gateway Switch Routing (CGSR) for clustered multi-hop mobile wireless network. In this protocol, nodes are arranged into clusters with each such cluster having its own cluster head. Nodes that lie within the communication range of two or more cluster heads, are called gateway nodes. Packets are first sent to the cluster head and then to the gateway and finally to other cluster head until destination cluster head is reached. Another strategy for dynamic networks is Global State Routing algorithm (GSR) [12]. Each node maintains its list of neighbours, a topology table, next hop table and a distance table. To avoid flooding of routing messages, generation of messages occurs on link change and nodes receiving these messages update their topology tables if the message's sequence number is new. It then reconstructs its routing table and broadcasts to its neighbors. To reduce the size of update messages, Chen et al. [13] introduced Fisheye State Routing (FSR). It overcomes the drawback of large size update messages associated with GSR. The message provides accurate information only about closer neighboring nodes instead of all of them. To overcome the drawback of mobility and location management, Iwata et al. [14] proposed Hierarchical State Routing (HSR), on the basis of multilevel clustering and logical partitioning. Nodes are organized into clusters each having its cluster head. Clusters are organized into levels. Lower level cluster heads become members of the higher level. Cluster head collects the information from its cluster and exchanges it with higher level.

David B. Johnson [15] proposed an on demand approach, Dynamic Source Routing (DSR). Each node maintains a route cache and updates it when new routes are discovered. This approach consists of two phases: route discovery and route maintenance. To send a packet, it first checks route cache. If found in it, the route is followed otherwise it initiates route discovery by sending a route request packet. A route is maintained using route error packet and acknowledgements. For reducing overhead of control messages, Park [16] proposed a highly adaptive loop free distributed routing algorithm known as Temporally Ordered Routing Algorithm (TORA). This routing protocol consists of three major phases: route creation, route maintenance and route erasure. In this protocol, a route is constructed using query (QRY) and update (UPD)

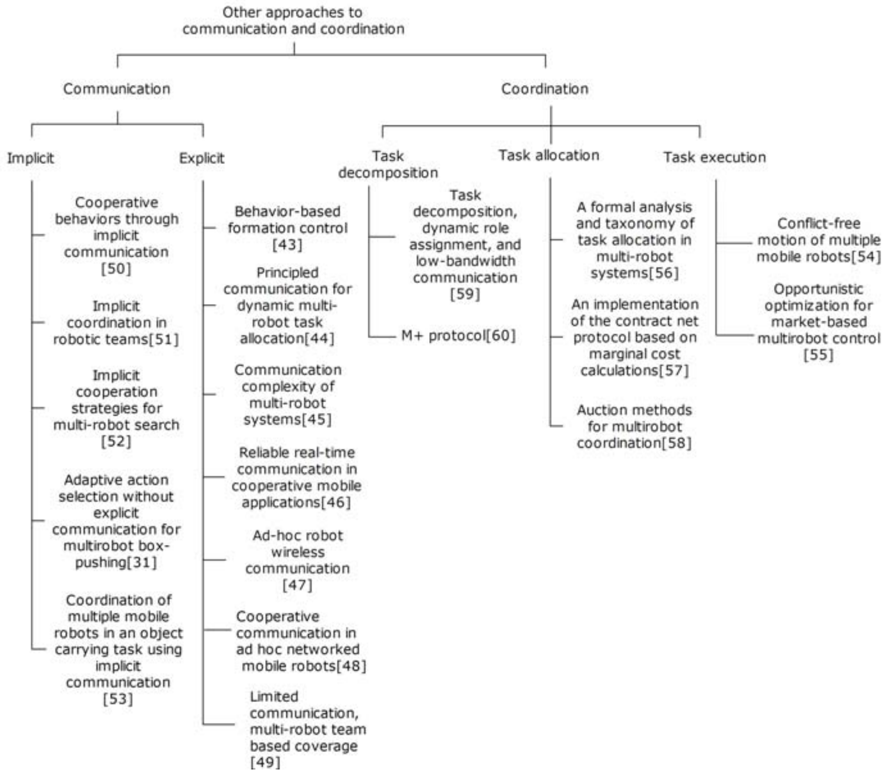


Fig. 2. Classification of the works done on robot communication and coordination

packets, maintained by re-establishing the broken Directed Acyclic Graph (DAG) route and erased by using clear (CLR) packet. Associativity Based Routing (ABR) is an approach to avoid loops while routing [17]. It introduced the concept of node's associativity state that implies period of stability. Each node generates a beacon, when a node receives the beacon it causes its associativity table to be updated. For every beacon received, it increments the associativity tick for the node from which it has received the beacon. To obtain stable routes between nodes, R. Dube et. al. [18] introduced Signal Stability-based Adaptive (SSA) routing, it is based on the concept of signal strength and location stability. The routes are selected on the basis of connectivity between nodes. SSA makes use of Dynamic Routing Protocol (DRP) as well as static routing protocol (SRP). DRP maintains the signal strength table and the routing table. DRP receives the packet and after updating the tables, it passes the packet to SRP. SRP then forwards the packet to the intended receiver. To reduce the number of broadcasts by creating routes only when required, a demand-driven algorithm Ad hoc On Demand Distance Vector Routing (AODV) has been introduced [19]. For route discovery process, the source node broadcasts a route request (RREQ) packet to its neighbors, which then forward the request to their neighbors, and so on until the destination or the intermediate node having information to reach the destination is reached. To reduce the number of routing messages, Young et al. [20] introduced Location Aided Routing protocol (LAR), based on location information. Location information is provided by Global Positioning System (GPS). It limits the routing search to a limited request zone. In this algorithm, a route is discovered using flooding. Mesut Gunes [21] introduced an on-demand routing algorithm Ant Colony Based Routing algorithm (ARA), based on the food searching behavior of ants (swarm intelligence). It consists of three phases: route discovery, route maintenance, route failure handling. In this algorithm routes are created using FANT (forward ant) and BANT (backward ant). They are maintained by recognizing duplicate packets with the help of sequence number. Alternative links are used to handle route failure. To prevent attacks, Y. C. Hu et al. [22] proposed a secure on-demand ad hoc network routing protocol Ariadne. It prevents the tampering of compromised nodes with uncompromised routes consisting of uncompromised nodes. The routing messages can be authenticated using one of the three schemes: secret keys shared between a pair of nodes, secret keys shared between communicating nodes along with broadcast authentication, or digital signatures. The paper discusses Ariadne with an efficient authentication scheme TESLA. TESLA adds a single authentication (MAC) code to the routing message, thus providing secure authentication. A brief description of the related survey with approaches [23]–[42] has been presented in Fig. 1.

Communication may also be divided into two alternative strategies, implicit and explicit. Explicit communication refers to the exchange of information between robots either by unicast or broadcast. Most of the present strategies use this mechanism. Implicit communication refers to the mechanism in which a robot acquires information about other robots from the environment. Related approaches [31], [43]–[60] have been underlined in Fig.2.

## III. Multi-Robot coordination

Various aspects of the problem of coordination in robots have been explored intensively in the past. Asama et al. [61] developed a generalized method of collision avoidance for a robot system. Firstly, robots try to avoid collisions based on rules to apply. If no rules are applicable, the robots need to negotiate by letting one to proceed first. In order to achieve coordination among the robots, Kennedy and Eberhart [62] developed the Particle Swarm Optimization (PSO) algorithm inspired by the social behaviour of swarms (such as insects, birds and fishes). The paper introduced the concept of distance and velocity update for particles in a search space if the current state is better than the present one. Poli et al. [63] proposed some optimizations to the original PSO algorithm to improve the optimality of the solution. An optimization suggested was introducing an additional factor of inertia weight. Constriction coefficient was introduced to improve convergence. In order to achieve coordination among robots in an efficient manner, Yamauchi [39] presented a way how can frontier-based exploration be extended to multiple robots. When a robot moves to a frontier, it explores the unexplored region and adds its map to the already existing map. Laser limited sonars were used to reduce the effect of specular reflections. A robot maintained a grid to represent areas, explored as well as unexplored. Another approach [40] was to select target points for different robots so that they explore different regions of environment. An additional factor introduced was utility. Its value reduces as soon as one robot chooses a target point. An approach to segmentation of the environment has been suggested in [64]. Robots are sent to respective segments to explore an area. The paper introduces frontier cells that assist in exploration and coordination of areas by multiple robots. In order to overcome obstacles in a robot's path, Albers et al. [65] presented an algorithm for exploring an unknown environment with obstacles. The algorithm is a generalization of the Ray algorithm that explores grids with rectangular obstacles. Energy efficiency had been an important area for research. To overcome power limitations in robots, Span-an energy efficient algorithm used for multi-hop ad hoc networks was developed [66]. Nodes are allowed to turn their receivers off when not in use. Some nodes may act as coordinators if they find that atleast two of its neighbours cannot directly communicate with each other. However to keep the number of coordinators low, a delay factor has been introduced which measures the time interval for which a node may defer its announcement to become a coordinator. Jonathan et al. [67] presented an approach to multi-robot map merging. In this approach, particle filters have been used to estimate the position of a robot in other robot's partial map. Before merging individual maps, robots must verify the relative locations. Ossama et al. [68] presented HEED-a hybrid energy efficient distributed approach for ad hoc sensor networks that considered clustering for efficient coordination in ad-hoc networks. After forming a cluster, cluster heads are selected based on the combination of node proximity and residual energy of a node. It aims at increasing the lifetime of the network. Mondada [69] presents a swarmbot or simply a swarm of multiple mobile robots. Each of the robots is autonomous in movement. Control strategies have been used to allow the swarm to move in a coordinated fashion. Zhangjun [70] has proposed a revised discrete PSO to schedule applications on cloud in which, velocity and position components are updated according to the following equation 1 and 2:

$$v_{id}^{n+1} = z(wv_{id}^{n} + c_1 r_1(p_{id}^{n} - x_{id}^{n}) + c_2 r_2(p_{id}^{n} - x_{id}^{n})) \quad (1)$$

$$x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n} \quad (2)$$

Where v, x, z, w denote the velocity component, position component constriction factor and inertia weight respectively. $c_1$ & $c_2$ are acceleration coefficients and $r_1$ & $r_2$ are random numbers generated in the ranges of $[0, 1]$. Here n denotes the index of the iteration.

Corke et al. [71] presented an approach how can robots co-operate within the network. A robot has been used to localize sensor nodes. These localized nodes are then used to navigate the robots in the space. In the robot-assisted localization algorithm, robot broadcasts its location regularly. Finally, the path stored in the sensor field can then be used for robot navigation. A control strategy has been proposed in [72] that allows robots to position themselves in such a way that reduces the sensory information used to drive the network to a desirable configuration. The robots need to sample a given scalar sensory function over the region. The value indicates the relative importance of different sub-areas in the region. If the value of sensory function is high for an area, it will receive observations of higher density. Various approaches proposed for multi-robot communication and coordination have been presented in the Fig. 1 and 2.

Another interesting and promising area in near future is Cloud Computing. Much of the focus has been laid on robotic communication and coordination using cloud. Yinong et al. [73] proposed robot as a service (RaaS) in cloud computing. RaaS has the complete functions of a Service-oriented architecture like a service provider, and a service broker. In our earlier work, [74] we presented 'Robot-Cloud' framework for heterogeneous low cost robots. We also presented that how a robotic components can also be presented as a service to build a robot. Moreover, this framework is also used to test user defined complex robotic algorithms over their builded robotic prototype [75]. Service catering has also been introduced as an additional functionality. Guoqiang et al. [76] proposed some of the Cloud Robotics based architecture, challenges and applications.

## IV. Proposed framework

As discussed in the previous section, with the advances of Cloud Computing, a more sophisticated and robust on demand applications of multi-robot co-ordination and communication can be developed. Unlike the frameworks for a single robot that makes the use of cloud [76], a multi-robot system that can make the use of Cloud simultaneously is desirable. In this paper, we have proposed a framework for cloud enabled communication and coordination among robots. In order to enhance the battery life and bandwidth utilization, all the robots are organized in the form of a cluster through CGSR protocol. Cluster head robots are responsible to pass the data of their underlined cluster robots to the Cloud. To leverage the advantages of both centralized and decentralized strategy, we have incorporated both of them. For a robot to communicate with another robot of the same cluster, it can directly communicate with it without the intervention of the cluster head (Decentralized) while robots in different clusters need to communicate via the cluster heads of their respective clusters (Centralized). The following subsection provides the detailed working of communication and coordination among robots.

### *A.* Communication among Robots:

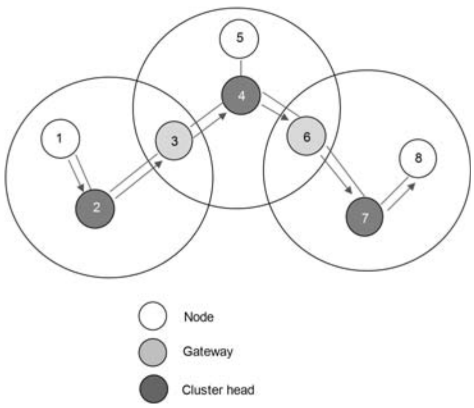


Fig. 3. Cluster Head Gateway Switch Routing

Robots are organized in various clusters and a cluster head is assigned from each cluster using CGSR protocol. In the cluster, each node periodically broadcasts HELLO messages containing its status. The routing process between the robots has been illustrated in Fig. 3 and described in the following steps:

*Step 1:*Initially for each node, the nodes in its marked list is set to NULL. Connectivity with other nodes is set to 0.

*Step 2:*A value for range is defined depending upon the arena for robots. In a larger area for navigation, range would have a greater value while for a smaller one, it would be smaller. If the Euclidean distance between two nodes is less than this value, the two nodes become neighbors.

*Step 3:*Connectivity of a node is compared with its neighbors. The node with the highest connectivity becomes the cluster head.

*Step 4:*The process is repeated for all the clusters.

### *B.* Multi-robot Coordination:

PSO is one of the well known algorithm which we have used for multi-robot coordination. In this algorithm, a fitness function is used to evaluate the state of a robot which determines the position and velocity with which it must move. Each particle maintains its $p_{best}[]$ (brackets signify multiple particles), which is the best value it had attained till that instant. If the computed value for the particle is better than the $p_{best}$, $p_{best}$ is set to this value. Also the particle with the best position so far is tracked and its position is stored as $g_{best}$. This is performed by assigning the index of the best value to $g_{best}$. The procedure is illustrated in Fig. 4.

Velocity and particle position are updated by the following equation:-

$$v_i = v_i + U(0, \Phi_1) \bigotimes (p_i - x_i) + U(0, \Phi_2) \bigotimes (p_g - x_i) \quad (3)$$

$$x_i = x_i + v_i \quad (4)$$

where $\bigotimes$ represents component-wise multiplication, $p_i$ denotes the $p_{best}$ position for the particle, $g_i$ denotes the $g_{best}$ position of the particle and U (0,$\Phi$) represents a vector of uniformly distributed random numbers in [0,$\Phi$]

A general working diagram of the proposed framework is presented in Fig. 5. It offers three types of communication models:

- Intra-cluster communication
- Inter-cluster communication
- Cluster to Cloud communication

In the intra-cluster communication, nodes lying within the same cluster communicate. This architecture is applicable to scenarios in which a node knows the shortest path to another robot within its cluster. It is known to its cluster head that the path discovered is the shortest. Hence the head need not be an intermediator for the route discovery. It saves the considerable overhead associated with the route discovery mechanism via cluster head.

Inter-cluster communication refers to the form of communication in which robots in different clusters communicate and co-operate with each other without the intervention of Cloud. This architecture is applicable to scenarios where a single cluster has insufficient number of robots to perform a task. Hence the involvement of more clusters adds the number of robots and hence the capacity to perform the task.

In the cluster to Cloud architecture, communication takes place between the cluster head and Cloud server. There are various computational intensive algorithms, which demand very sophisticated computation or are required to be executed at the earliest. This type of situations can be well handled by offering Cloud-based services. Moreover, a Cloud can also offer the services to a robot at run time for which it was not designed for [74]. Simultaneous Localization And Mapping

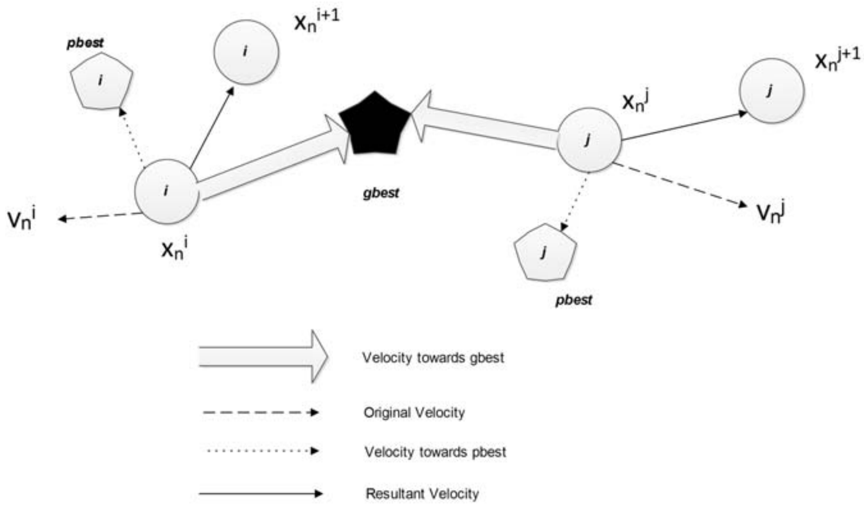


Fig. 4. Illustration of Particle Swarm Optimization

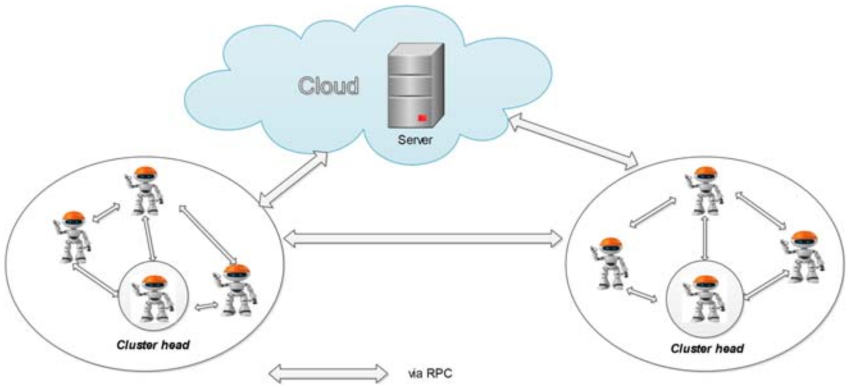


Fig. 5. Proposed architecture of the environment

(SLAM) is one of the such example which requires very high computation and storage [77].

In our framework, all the robots are registered with the Cloud server. Only registered and authenticated robots can use the Cloud services. Cloud maintains a list of functionalities that it can offer to a variety of robots. Cloud server first checks the compatibility of the robots with its offered services then it sees whether the resources are available or not. It only provides the service if the robot is registered, has a service to offer and resources are available. It puts the request for the services in the queue if the services is already engaged with other robot. TCP/IP protocol stack is used for communication between robots and Cloud server. Robots communicate through message passing with other robots or with Cloud and this is done over Remote Procedure Call (RPC). In this system, all the robots marshal their sensory data with client stub and send to the other robot or Cloud with the help of their cluster head robot, which de-marshal the data and call the intended procedure for execution. When the response is ready it is forwarded to the requesting cluster head robot. However, after getting the response from the Cloud server, cluster head robot has to send the response to the actual requesting robot. As discussed in Section 3, all the robots coordinate their actions and movement according to the velocity and position components defined by PSO, which provides convergence towards the goal while being in a cluster and avoid collision with other robots.

## V. Conclusion

In this paper, we have systematically surveyed and analyzed various communication and coordination approaches proposed for multi robot environment. The investigation of the related literature shows that considerable progress has been made in the field of robotic coordination and communication. We initiated the paper by giving a brief overview of the communication approaches developed so far for robots in an environment. Following this, coordination approaches proposed for robots till date have been outlined with a brief overview of each of them. Two decision making strategies have been identified for coordination- centralized and distributed. Based on our review, some promising avenues for research are available:

- Much attention has been paid to coordination between same types of robots. Hence an interesting area would be to enable coordination between different kinds of robots.
- Secondly energy consumption along with performance must be of utmost importance in future.
- Both the centralized and distributed approaches of coordination have their own pros and cons. Thus it would be efficient to build a hybrid mechanism.

Finally, we proposed a framework that we intend for enabling communication and coordination among robots through Cloud where PSO and CGSR are used for coordination and communication by forming clusters of robots.

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