A Survey of Multi-mobile Robot Formation Control

Bayadir A. Issa
Electrical Engineering Dept.
University of Basrah
Basrah, Iraq

Abdulmuttalib T. Rashid
Electrical Engineering Dept
University of Basrah
Basrah, Iraq

ABSTRACT
This paper denotes a survey on formation control of multi-mobile robot systems which drawn significant attention for the last years. It is concentrated on the stability of multi mobile robots when they obtained the required formation. Also this paper discusses the approaches of formation control and applications of them in changing and remote environments. Two classifications for the formation control methods are surveyed in this paper: the formation control strategies and the formation control stability. The differences among the surveyed approaches are discussed and the results are summarized.

General Terms
Formation, Multi-robot system

Keywords
Formation control; Multi robot; Behavior based approach; Leader follower approach; Virtual structure approach

1. INTRODUCTION
The robot formation can be define as branch of robotic system which studies the coordination of a group of mobile robots to give a formation with assured shape. This formation of robots are used to perform collective tasks. The robot can perform the task alone or implemented more completely by the robots are bevy [1]. Group works of multi mobile robots include transportation of objects, field inspection, and environmental surveillance. All these tasks have practical applications in today's population such, salvage missions in crash and exactness agronomy [2]. In the utmost years, the multi mobile robots have been used in distinct field of applications including essence localization [3], mobile sensor network, and medical operations [4]. These application are more complex and difficult to be determined. The problems on how to implements these operations and controlling a group of robots to make them to move as a group to perform their tasks in good manner and fundamental one.In order to fulfill the goal of formation, several problems have to be solved. These problems are: the problem of knowing the initial position of these robots, and the path planning from initial to the final locations in formation. This process also needs to deal with obstacle avoidance and collision avoidance, when robots move to their final location. Different localization approaches have been designed to work in local and global knowledge environments with different types of range sensors, such as IR sensor, ultrasonic sensor, sonar and laser range finders [5-9]. These localization approaches are very important to perform the formation of multi-robot, since they are produce the initial position and orientation of each robot in environment. Also, the Path planning approaches are important aspects of multi-mobile robot formation. These approaches can be classified into global and local methods based on the sensor information available [10-11]. The global methods guarantees the reaching of the robots to their targets. On the other side, the local methods which based on sensing range of the sensors do not guarantee the reaching of the robots to their targets [12].

Perform the formation operations as a group of movement are classified in to two parts; grouping and controlling the formation. Controlling the formation of a group of multi mobile robots means how to stabilize and maintain a desired formation shape in a distributed manner as shown in Fig. 1.

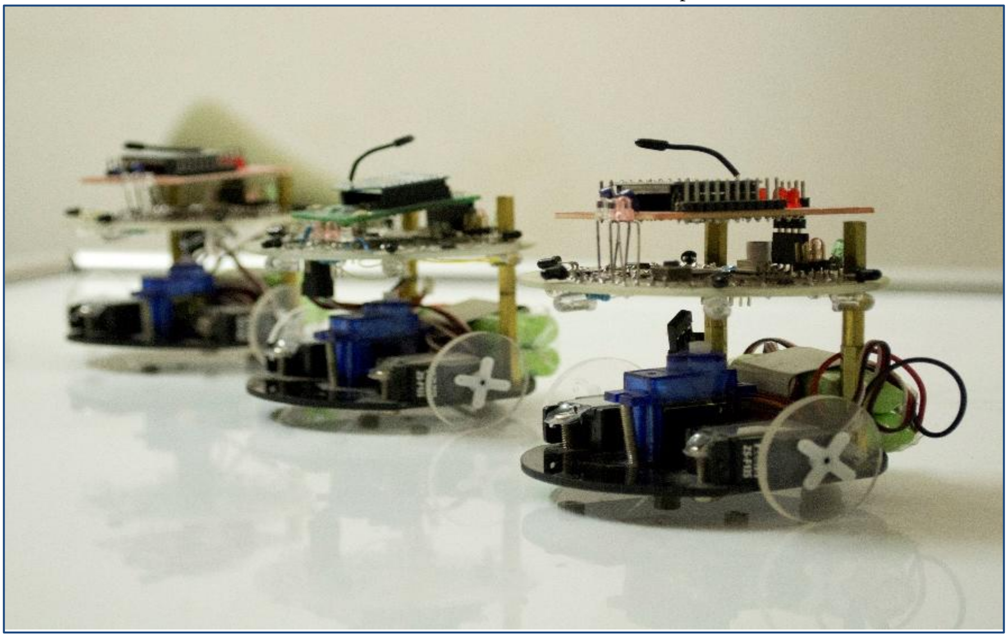

Fig. 1. The group of robots formation.

The formation control according to several researches can be classified as leader follower strategy [13], virtual structure approach and behavior – based approach [14]. Also the characterization for the control formation methods in terms of the sensing capability and interaction topology generally breeds to the inquiry of what variables are sensed and what are actively controlled by robotic systems to obtain their wanted formation. These variables determine the desired on the sensing capability of single robot. Also the types of controlling variables are essentially connected to the interaction topology. Shortly the type of controlled variables determine tops possible wanted formation can be obtained by robots which is the desired on the interaction topology of the robots.[15]

2. THE FORMATION STRATEGIES

Many researches on swarm robots have concentrated on formation control, which defines as the task of controlling swarm of robots to avoid collisions and manage the desired formation pattering and its operation in aggressive environment and remote. So the approaches that have been considered for controlling the formation can classified into three basic approaches:

2.1 Behavior based approach

Behavior based approach is decentralized control method used to control one or more robots in group; note that the decentralized control method means there is no planning or reasoning to generate the responses [16]. Means there is no central part mange the system. So its implemented with less communication, behavior based approach make the robots drive the controls for multiple computing objects at the same time [15]. Also in behavior based approach several states are prescribed for each robot and the final control is derived from a weighting of relative importance of each state [17]. The motion trajectory for each robot in this approach is generated by computing the average of the motion primitive for each the Obstacle avoidance, formation investigation and target arrival as shown in Fig. 2.

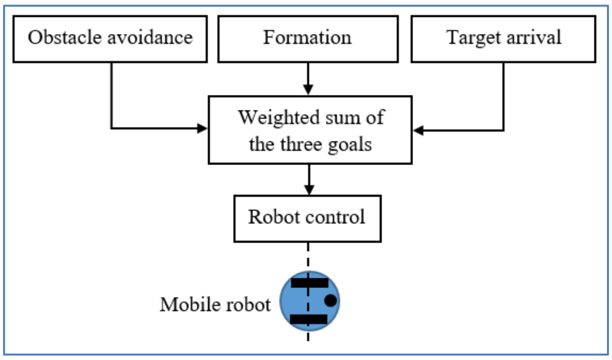

Fig. 2: The Behavior based approach.

In [18] the formation in multi robot system are implemented with behavior based method which integrated with other navigational behaviors to enable a team of robots to access the goals and obstacle avoidance.In [19] the behavior based approach are implemented to control the formation of swarm robots while navigated in unknown area and obstacles. In [20] behavior based team work architecture that automates collaboration in physical robots, in distributed fashion. This method provide the flexibility by separating behaviors that control social interactions from those that mange subtask. In [21] in the global behavior is obtained in a group of distributed robots using only local sensing and minimal communication. In [22] control formation for group of robots which is formed approximations to circle and simple polygons using global knowledge of all robot's positions. The main disadvantage of this method is that the mathematical analysis of this approach is complex and therefore the concurrence of the robotic formation to the desiderated structure cannot be approved. But this method have advantages design reaction is essentially unified by pairing the weights of the actions that depends on the reciprocal counterparts of the adjoining robots. And proper in leading the multi robotic system in unknown or changing area by using acoustic information only.

2.2 Leader follower formation approach

In leader follower method the robot in formation designed as a leader move along a predefined trajectory while the other robots (the followers) are to maintain a desired formationIn [22] a stable leader follower formation control low is investigated based on kinematic model and trajectory tracking technique. Stability of control low is proved through the use of lyaponuv function (rotation and translation) to the leader as shown in Fig. 3 [23]. The advantage of this method: it’s easy to understand and implement, also this approach has some disadvantages it asks for centralized control approach (follower use the position of leader as input control), which make it less suitable for large number of robots. There is no explicit feedback from the follower to the leader. For example if the leader moves to fast, or if the follower is blocked by an obstacle the formation will be destroyed. Another disadvantage is that if the leader has failed, the entire formation cannot be kept and the consequence will be very serious. In [24] a formation focuses on the problem of vision-based leader-follower control of mobile robots. The proposed adaptive controller only requires the image information from a non-calibrated perspective camera mounted at any position and orientation (attitude) on the follower robot. Furthermore, the approach does not depend on the relative position measurement and communication between the leader and follower. A new real-time observer is developed to estimate the unknown intrinsic and extrinsic camera parameters as well as the unknown coefficients of the plane where the feature point moves relative to the camera frame.

In [25] leader follower formation are used to perform static and moving obstacles. The performance of this method is converge stability. The multi robot system are decomposed into several leader follower pairs, in each pair the leader takes charge of tracking a predefined trajectory while the followers keeps track of the leader and maintains the desired distance and relative angle, also the follower robot must be able to follow any path described by the leader robot while maintaining a constant distance with respect to it. Therefore, the design of the control strategy should be based on the follower’s control signals.

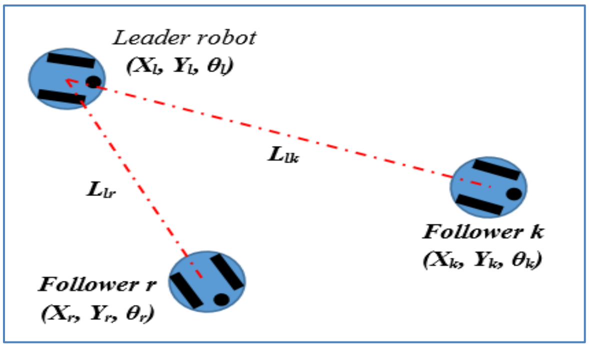

Fig 3: The leader follower approach

2.3 Virtual structure approach

In virtual structure approach the entire formation is regarded as a single structure where each robot is given a set of control to follow the desired trajectory of formation as rigid body as shown in Fig. 4. The main advantages of this approach is that a single mathematical rule translate the entire sensory input space into the actuator output space without the need of multiple rules or behaviors. Also, the obtained behaviors can be combined using vector operations. Some properties such as robustness and stability can be proved using the theoretical tools from physics, control theory and graph theory [26]. Also, the virtual physics-based method is often used to design collective behaviors that require multi robot formation.

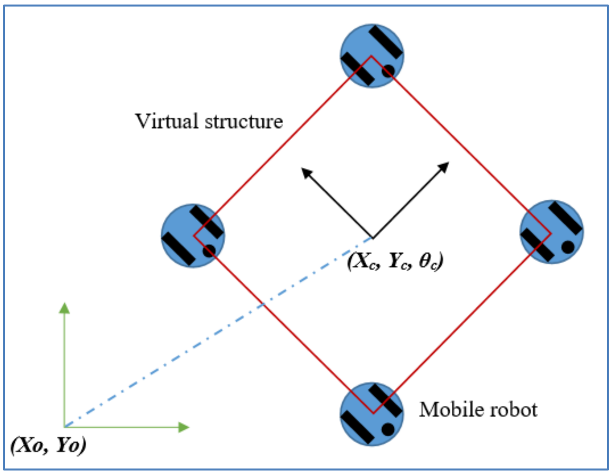

Fig. 4. The virtual structure.

2.4 OTHER FORMATION CONTROL APPROACHES

Other formation control methods are served and compared in terms of sensing capability and the interaction topology among which three most commonly used methods are:

2.4.1 The displacement-based approach:

the robots actually control displacement of their neighboring robots to obtain the desired formation. This formation is specified by the desired displacements with respect to global coordinate system under the assumption that each robot is able to sense relative positions of its neighboring robots with respect to the global coordinate system. This intends that the robots need to know the orientation of global coordinate system and their position with respect to the coordinate system.

2.4.2 The distance based approach:

inner robots distances are actually controlled to obtain the desired formation, which is given by the desired inner robot distances. The robots are assumed to be sense relative positions of their neighboring robots with respect to their own local coordinate systems. These robots are not necessarily to be aligned with each other.

2.4.3 Position based approach

the robots sense their own positions with respect to a global coordinate system [15].

3. FORMATION CONTROLSTABILITY

The formation stability problem has generally been studied by the lyapunov stability theory and graph theory.

3.1 Lyapunov theory

Controlling the formation and interaction stability have been studied in recent time for various aspect. In [27] a stable coordination strategy for a team of formation constrained autonomous robots. The lyapunov formation function is used to prove the properties such as formation maintenance, task completion time, and formation velocity. Also in [28] the stability of formation control for non-holonomic robots are analyzed by lyapunov function. A novel decentralized consensus based formation controller are considered. The network which consist with N robots are modeled as undirected, static and connected graph. The stability of controller was generated by lyapunov function. The lyapunov stability theory is a method of analyze the overall formation stability, which is defined as a weighted sum of control lyapunov function for each vehicle to support the formation stability analysis. It is also used to design the decentralized controllers along the extended linear matrix in equality to analyze the conditions required for formation stability [29].

3.2 Graph theory

Another way of analyze the formation stability is graph theory which is used to drive the control system of multi robot system to define the physical relations between the individual robots. Using the graph theory is seen to be greatly beneficial because the algorithm have been developed to find the rigid and minimally-constrained structures [30]. In graph theory a graph is consist with a set of vertices (nodes) and edges (links) which connects the vertices as shown in Fig. 5. A graph is generally showed with the notation of *G (E, V)* which is a data structure of the set of vertices (*V*) and edges (*E*). V and E are usually taken to be finite and they represent different meanings. For example, vertices may have the locations of objects and edges may represent any relations between vertices such as a flux of energy.

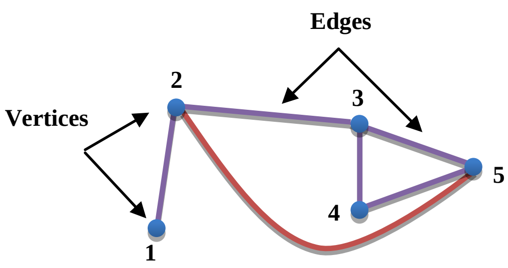

Fig. 5. The graph structure.

In mathematical view, the undirected graph *G (V, E)* is made of a set of vertices (a finite set of elements).

$$V = \{v_1, v_2, v_3, \ldots, v_n\} \tag{1}$$

An edge set is a subset of unordered pairs of V^2 ;

$$V^2 = \{(V_i, V_j)\};\ i = 1,2,\ldots,N;\ j = 1,2,\ldots,N; i \neq j. \tag{2}$$

For a graph shown in Fig. 2:

$$V = \{v_1, v_2, v_3, v_4, v_5\} \tag{3}$$

$$E = \{(v_1, v_2)(v_2, v_3)(v_2, v_5)(v_3, v_4)(v_3, v_5)(v_4, v_5)(v_4, v_5)\} \tag{4}$$

The G is a graph can be simple, multi graph, digraph, weighted graph…). The adjacency matrix which is represented by the equation 5.

$$A = (a_{ij}) \quad (5)$$

It is written as

$$A(i,j) = 1 \;;\; iff\; (i,j) \in E \quad (6)$$

For graph in Fig. 2

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (7)$$

Another matrix used in graph theory which is called incidence matrix. Which is show the relation between the vertices and edges. If we choose the rows for representing the vertices, columns represent the edges. The matrix has only two ones in column if the edge are all connected to a vertex in both endings.

For the graph in figure 1 the incidence matrix *T*

$$T(i,k) = T(j,k)=1 \;;\; iff\; e_{k\,(vi,vj)} \quad (8)$$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \quad (9)$$

Also, there's another important aspect is a degree of graphs which represent d (v) is the number of $vi, vj \in E$. [30-32].

4. CONCLUSION AND FUTER WORKS

Many research on multi robot collaboration have concentrated on controlling the formation group of mobile robots to follow pretend path while keeping the wanted formation patron. Different control methods have been expected and enforced to the planning design of robotic systems, such that behavior based approach, virtual structure approach, leader follower approach.When the comparison is with the virtual structure approach, leader follower approach can grasp time- varying formation method. Even under complex conditions such as unknown disturbances, uncertain parameters. Its guarantee formation stability. It's easier grasp in practicable applications. But one problem with leader follower is that if the leader is failed the entire system will fail [15]. It's excluded as a centralized scheme. There still exits a number of problems with the controlling the formation of multi robot system including the stability analysis and applications in unknown environments.Controlling the formation in dynamic and unknown are requires method that can deal with insecure positions. The control methods must contain the stableness properties. Easy algorithm and fewer calculation capability the control formation must be contained. The simple control algorithm with little processing speed and memory space is required.In multi robot system to obtain the secure path for all robots in unknown area using robust algorithm in which each robot contains local measurements from laser scanner. So the robot not require to exchange any information with the others and not require communication channels so this helps the scaling of overall system to a large number of robots. The robot need only the relative position with respect to their neighbors. The second important aspect that being disfavored in controlling system is implementation and testing. In most case using computer simulation.A survey of multi robot formation control are presented in this paper with number of last studies. Controlling the formation of multi robot system were analyzed and resolved by intelligence and optimization methods.

5. REFERENCES

[1] A. Handayani, S. Nurmaini, N.Husni, and I.Yanithe "survey paper: formation control for swarm robots." Proceedings of the International Multi Conference of Engineers and Computer Scientists 2016 Vol I, IMECS 2016, March 16 - 18, 2016, Hong Kong.

[2] H. Garcia de Marina, J. Siemonsma, B. Jayawardhana, and Ming Cao "Multi robot-motion formation distributed control with sensor self-calibration", unmanned Aerial Systems Center, University of Groningen, the Netherlands. IEEE. 2018.

[3] T. Lochmatter, X. Raemy, and A. Martinoli, "Oder source localization with multi robot system" Swarm-Intelligent Systems Group, Vol. 112, pp. 123-136. 2019.

[4] P. Orgen, "split and join of vehicle formation doing obstacle avoidance", IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004

[5] A. T. Rashid, M. Frasca, A, A, Ali, A. Rizzo and L. Foruna," Multi-robot localization and orientation estimation using robotic cluster matching algorithm. Robotics and Autonomous Systems, Vol. 63, p.p. 108–121, 2015.

[6] O. A. Hasan, A. T. Rashid, R. S. Ali and J. Kosha," A Practical Performance Analysis of Low-Cost Sensors for Indoor Localization of Multi-Node Systems ", Internet Technologies and Applications (ITA), Wrexham UK, September 2017.

[7] O. A. Hasan, A. T. Rashid and R. S. Ali," Centralized approach for multi-node localization and identification ", Iraq J. Electrical and Electronic Engineering, Vol.12 No. 2, pp. 178-187, 20 1 6.

[8] O. A. Hasan, A. T. Rashid and R. S. Ali," A Hybrid approach for multi-node localization and Identification ", Basra Journal for Engineering Sciences, vol. 16, no. 2, pp. 11- 20, 2016.

[9] A. T. Rashid, W. H. Zayer and M. T. Rashid," Design and Implementation of Locations Matching Algorithm for Multi-Object Recognition and Localization", Iraqi Journal of Electrical and Electronic Engineering, Vol. 14, No. 1, p.p. 10-21, 2018.

[10] A. T. Rashid, A. A. Ali, M. Frasca and L. Fortuna, " Path planning with obstacle avoidance based on visibility binary tree algorithm," Robotics and Autonomous Systems, vol. 61, pp. 1440–1449, 2013.

[11] Z. Y. Ibrahim , A. T. Rashid, and A. F. Marhoon, " An algorithm for Path planning with polygon obstacles avoidance based on the virtual circle tangents", Iraq J. Electrical and Electronic Engineering, Vol. 12, No. 2, pp. 221-234 , 2016.

[12] Z. Y. Ibrahim , A. T. Rashid, and A. F. Marhoon, " Prediction-Based Path Planning with Obstacle Avoidance in Dynamic Target Environment ", Basra Journal for Engineering Sciences, Vol. 16, No. 2, pp. 48 – 60, 2017.

[13] D. Qian, S. Tong, J. Guo , and S. Lee "leader follower formation control of multi robot with uncertainties through sliding mode", June 2015 Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems and Control Engineering 229(6), 2015.

[14] Z. Sun, "cooperative coordination and formation control for multi agent system", Springer International Publishing AG 2018, 2017.

[15] K. K. Oha, M.C. Park , and H.S. Ahnb,"A survey of multi agent formation control", Automatica, Vol. 53, pp. 424-440, 2015.

[16] T. Soleyman and F. Saghafi "Behavior-based acceleration commanded formation flight control", International Conference on Control, Automation and Systems 2010 IEEE, 17 December 2010.

[17] J.R.T. Lawton, R.W. Beard and B.J. Young "A decentralized approach to formation maneuvers", IEEE Transactions on Robotics and Automation, Vol. 19, No. 6 , Dec. 2003.

[18] T. Balch, R.C. Arkin "Behavior based formation control for multi robot team" IEEE Transactions on Robotics and Automation, Vol. 14, No. 6, Dec 1998.

[19] D. Xu, X. Zhang Z. Zhu, P. Yang "Behavior based formation of swarm robot", Mathematical Problems in Engineering, DOI: 10.1155/2014/205759, 2014.

[20] G. A. Kaminka and I. Frenke "Flexible teamwork in behavior –based robots", Proceedings, The Twentieth National Conference on Artificial Intelligence and the Seventeenth Innovative Applications of Artificial Intelligence Conference, July 9-13, 2005,

[21] J. Fredslund, and M. Matari´c "A general algorithm for robot formation using local sensing and minimal communication", IEEE Transactions on Robotics and Automation, Vol. 18, No. 5 , pp. 837-846, 2002.

[22] K. Sugihara and I. Suzuki, "distributed algorithm for formation of geometric patterns with many mobile robots", John Wiley & Sons, Inc.1996.

[23] L.Consolini, F. Morbidi, D. Prattichizzo, and M. Tosques, "A geometric characterization of leader –follower formation control." Proceedings 2007 IEEE International Conference on Robotics and Automation. Roma, Italy, 2007.

[24] H. Wang, D. Guo, X. Liang, W.Chen, G. Hu and K. Leang " Adaptive Vision-Based Leader–Follower Formation Control of Mobile Robots", IEEE Transactions on Industrial Electronics, Vol. 64, No. 4, April 2017.

[25] S. Nouyan, and M. Dorigo "Path formation of robotic swarm", Swarm Intelligence, Vol.2, No. 1, pp. 1-23, 2008.

[26] L. Barnes, M.David Fields, and K. P. Valavanis "Unmanned ground vehicle swarm formation control using potential field" Mediterranean Conference on Control 2007.

[27] P. ogren, M. egrested, and X.Hu "A control lyapunov function approach to multi agent coordination ", Proceedings of the 40th IEEE Conference on Decision and Control, Cambridge. USA, 2002.

[28] M. Maghenem ,A. Castillo E. Nuño, A. Loría, and E. Panteley "consensus-based formation control of non-holonomic robots using a strict lyapupov function", IFAC-Papers On Line, Vol. 50, No. 1, pp. 2439-2444, 2017.

[29] A. Yang, W. Naeem,G. Irwin, and K. Li "Stability analysis and implementation of a decentralized formation control strategy for unmanned vehicles" IEEE Transactions on Control Systems Technology, Vol. 22 , No. 2 , March 2014.

[30] J.Barca, A.Sekercioglu, and A.Ford "Controlling formation of robots with graph theory", Intelligent Autonomous Systems 12, AISC 194, pp. 563–574. Springer-Verlag Berlin Heidelberg 2013.

[31] K. erdogan, M. korkmaz, A.durdu, N. ylmaz and S. topal "Formatting morphing of multi robots using graph theory", Proceedings of the World Congress on Engineering and Computer Science 2015 Vol I WCECS 2015, October 21-23, 2015, San Francisco, USA.

[32] J. C. Barca, A. Sekercioglu, and A. Ford" Controlling Formations of Robots with Graph Theory", Advances in Intelligent Systems and Computing, Vol. 194, pp. 563-574, 2013.