Swarm Robotics: Remarks on Terminology and Classification

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Abstract. Swarm robotics is a fast-growing field of research in recent years. As studies count increases, the terminology requires a revision in order to provide a proper level of unification and precision - even a unique "swarm robotics" term needs to be established. Since there are multiple types of collective robotics approaches and corresponding methodology, swarm robotics field terminology must be explicitly distinguished from others. In this paper, we attempt to compare and refine definitions that had been proposed in previous researches. We demonstrate relations between swarm robotics and concepts of adjacent fields including multi-agent systems, multi-robot systems and sensor networks.

Keywords: Swarm robotics · Sensor network · Robotic group
Multi-agent system · Multi-robot system

1 Introduction

Swarm robotics is one of multiple forms of robotic groups. Terms like a "multi-robot system", a "multi-agent system" and a "sensor network" are frequently used in researches that are dedicated to robotic groups. These terms are often perceived as synonyms although there are some important differences between them. As the field is still establishing itself, the basic terms of swarm robotics vary from one paper to another and this must be carefully considered. For example, groups of multiple robots are denoted in various recent studies as:

- Multi-Robot System (MRS) [3,12,16,30]
- Multi-Agent System (MAS) [9,13,20,25,29]
- Swarm Robotics System (SRS) or Robotic Swarm (RS) [4,10,14,15,21,22]

There are a few other terms used to express similar, yet not the same, meaning in robotic field studies. Researchers often use terms like "collaborative robots" [1], "sensor network" [23] to denote groups of mobile robots or/and mobile sensors. In addition, there is very special "weak robot" term [6,8] that was used primarily in the early beginning of the 21-st century. It mostly disappeared

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in recent studies; yet, it should be mentioned since weak robots have a lot of similarities with swarming robots and the results of weak robots researches could be applied in swarming robotic systems development. This paper is dedicated to an attempt of defining a unique "swarm robotics" terminology and distinguishing it from other terms being used in the field of robotic groups. Furthermore, we structure and compare the previously proposed definitions and terminology of the field.

One of the first studies that mentioned swarm robotics as a distinct term was a paper by Gregory Dudek et al. [7] published in 1993. This study was one of the major triggers for multiple researches, which targeted for analyzing and classifying multi-agent systems. However, "swarm" definition and classification that were proposed by Dudek et al. were not globally accepted by subsequent authors. For instance, Sigihara et al. [26] and Suzuki et al. [27] used such terms as "many mobile robots"and "distributed anonymous mobile robots" in order to define robotic group capabilities as accurate as possible. Other attempts to identify "swarm robotics" term were made by Beni [1] and Sahin [23] in 2004. These studies distinguished robotic swarms between other forms of group robotics and proposed sets of properties to identify swarm robotics. These properties mostly remain constant until recent studies of swarm robotics done by Tan et al. [28] and Navarro et al. [19] in 2013.

2 On "Swarm Robotics" Term

As it was mentioned in the previous section, Dudek et al. first defined "swarm" term in a context of robotics in "A taxonomy for swarm robots" research paper. They referred to Beni's paper [2] that had been published in 1989 as to the origin, which had suggested to use a word "swarm" for a robotic group type. Dudek et al. proposed swarms classification that was based on multiple properties such as swarm size, inter-robots communication range, control topology, swarm homo- or heterogeneity. "Swarm" was defined as "a large number of smaller, simpler robots". However, the paper included multiple cases of using "swarm" term as a synonym to terms "multi-robot system" and "multi-agent system". It shows that swarm robotics concept was not yet established uniquely by that time. However, Dudek et al. proposed a reasonable taxonomy of MRS, which is still actual: this taxonomy was even used after two decades by Navarro et al. to separate swarm robotics from other types of MRS.

Next major attempt to define swarm robotics and classify it was made by Beni in 2004. He mentioned swarm robotics as a distinct field of robotics research and defined swarms through a set of the following requirements to be met in order to call a group of mobile robots "a swarm" [1]:

1. A swarm has a scalable architecture: there is no strict requirements for a swarm to include a large number of members
2. Inter-robot communications and sensing are limited to be only local
3. Scalability requirement determines distributed control topologies usage
4. Members of a swarm must be simple and quasi-identical

All these properties still remain in recent swarm robotics definitions and have only additions and refinements.

Sahin [23] made his research on swarm robotics terminology at the same time with Beni and specified a robotic swarm more precisely, excluding some types of collective robotics terminology from swarm terminology. In addition to all properties of Beni some new clarifications were proposed. Swarm members "simplicity" property was replaced by a "relative incapability" property; this definition is more precise because term "simple" is vague and it is hard to conclude unambiguously, for instance, if a particular type of quadcopters (that are often employed in swarm related researches) is simple or not. The quadcopters' capabilities may be significantly limited relatively to a task size, but even these capabilities may require complex hardware and software to operate in synergy. Next, Beni required swarm members be autonomous in a such way that they should be able to perceive information from an environment and interact with the environment autonomously. For instance, this requirement excludes sensor networks from swarm robotics. This is reasonable because of sensor networks dissimilarity with natural swarms, which inspire robotic swarms. Table 1 presents main properties of different definitions in an easy for their simultaneous comparison form.

Table 1. Swarm robotics properties according to previous researches

Dudek et al., 1993	Beni, 2004	Sahin, 2004
large number of members	scalable	aim for scalability
simple and small	simple	relatively incapable
inter-robot communication	local interactions	local sensing and communication
	decentralized	distributed
	quasi-identical members	a few homogeneous members
		autonomous

Tan et al., 2013	Navarro et al., 2013
large number of members	large number of members or scalable
mostly simple	incapable or inefficient
local sensing and communication	local sensing and communication
decentralized	distributed
homogeneous	mostly homogeneous
autonomous	autonomous
	cooperative
	knowledge aware
	strongly coordinated

A number of researchers provide similar to Sahin [23] concepts of swarm robotics (e.g., [19,28]) that specify the following properties:

- Scalability. Swarm architecture must be designed to be applicable with both small and large numbers of robots. This is essential for robotic swarms which are, theoretically, could have an unlimited count of members.
- Members simplicity. A single member of a swarm is incapable to perform a common swarm goal alone or/and multiple robots usage should significantly increase efficiency of a task performance. Therefore, achievement of the goal becomes dependent on the inter-swarm (i.e., inter-robot) communication quality and effectiveness.
- Local interactions. All sensing and communications are only local. This property is directly inherited and transferred into robotics from natural swarms: insects, fishes and birds are not capable to perform global measurements. Local interactions usage is a key to an easy scalability of a swarm; this increases the swarm robustness and flexibility.
- Control topology is distributed. Centralization limits scalability, therefore, all decisions should be made by swarm members independently.
- A swarm consists of a number of homogeneous robots. The swarm must easily overcome a loss of any of its members. The only way to provide such robustness is to make all swarm members as similar to each other as it is possible. This similarity gives both functional robustness and economical effect when a swarm cost decreases because of standardization.
- Autonomy: robots must be capable to perceive data from environment and interact with it. This property may seem obvious and redundant, however, it explicitly excludes sensor networks from swarm robotics.

In addition, Navarro et al. reference to MRS classification by Iocchi et al. [11] declaring that a swarm is a cooperative, knowledge aware and coordinated MRS and thus should feature the following properties:

- Cooperation. A situation in which several robots operate together to perform some global task that either cannot be achieved by a single robot, or whose execution can be improved by using more than a single robot, thus obtaining higher performance.
- Awareness. The property of a robot that reflects its knowledge about the existence of the other members of the MRS.
- Coordination. A sort of cooperation where particular actions that are performed by each separate robotic agent (viewed locally) take into an account the actions, which are executed by the other robotic agents in such a way that the MRS activity (viewed globally) ends up being a coherent and high-performance operation.

These properties need to be analyzed separately. Declaration of awareness is too strict for robotic swarms: as it is shown in [17,24], a swarm may have all the above mentioned properties, yet members of the swarm may perform tasks without knowledge about other members' existence. Moreover, a partial or complete unawareness cannot stop coordination processes [24], and robots of the swarm just react on other swarm members, as if the later were static or dynamic obstacles of the environment. A particular example in [17] demonstrated that even without inter-swarm coordination it is possible to perform a task of environment exploration. At the expense of optimality, the simplest robots could show swarming behavior. It is worth to note that swarm coordination is not always observed even in nature, for instance, insects in a case of high risk could act like distinct members, ignoring other swarm members and trying to stay alive even at the expense of other swarm members. Therefore, it seems unnecessary for swarming behavior to be coordinated and knowledge aware.

Nevertheless, the cooperation is very important to define swarm robotics properly. This property effectively excludes (from the swarm definition) such groups of robots that are not united to achieve the common goal. For example, a sequence of manipulators on a conveyor are not a type of a robotic swarm.

3 Swarm Robotics Relations with Other Collective Robotics Terms

This section explores the differences between various terms that are frequently used by researchers to denote groups of mobile robots and robotic swarms. Each subsection includes a clarification, which is related to some terms and a scheme in Fig. 1 combines our findings into a single structure.

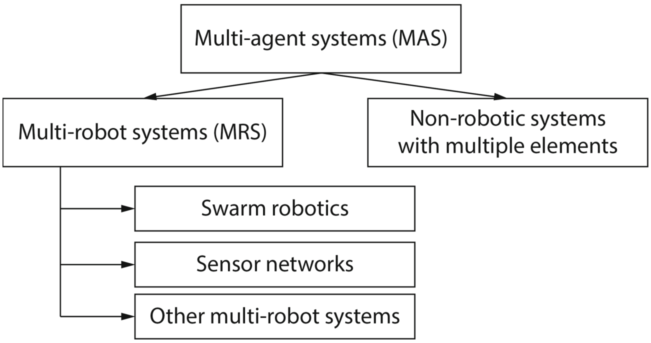

Fig. 1. Proposed relations scheme between MAS, MRS, sensor networks and robotic swarms.

3.1 Swarm Robotics Vs. Multi-robot Systems and Sensor Networks

Dudek et al. [7] use the three terms - robotic swarm, Multi-Robot Systems (MRS), Multi-Agent Systems (MAS) - as synonyms. Therefore, their pioneering approach was rather far from a modern understanding of swarm robotics definition, which, as we have described in the previous section, became very precise and well-defined with time.

First, we explore the differences between MRS and swarm robotics. Iocchi et al. [11] studied specifically MRS and proposed a very comprehensive MRS taxonomy. After more than a decade this taxonomy was used by Navarro et al. [19] to set the place of swarm robotics among other MRS. MRS in this context is a system containing multiple robots. This definition includes a very wide range of robots; for example, it includes both teams on the robotic soccer match as whole or sequential industrial manipulators on conveyor line. The provided examples are only multi-robot systems, they do not have any of the collaborative or swarm robotics properties that we have mentioned in the previous section. Swarm robotics studies multiple robots; therefore, it is worth concluding that any robotic swarm is a multi-robot system but not vice versa. Beni [1] also proposed to consider swarm robotics to be included into multi-robot systems as a subset. Such inclusion seems logically correct and, in our opinion, remains true.

Sahin [23] suggested a next clarification, explicitly excluding sensor networks from swarm robotics. This was made by adding the autonomy requirement to the definition of a swarm. Sensor networks members cannot interact with environment, and therefore, they are not autonomous in terms of Sahin. However, sensor networks are still a subset of multi-robot systems.

3.2 Swarm Robotics vs. Multi-agent Systems

A term "multi-agent systems" is not a purely robotics term, but is very broad and includes various non-robotic groups as well. It may be used to describe biological structures like insects colonies (ant, bees, termites, etc.), mammals societies, subjects of interest in psychological studies (people crowds, worker teams), economic theories participants and more others. In robotic studies, this term is used primarily in cases when a system is analyzed through ideal models of robotic members. Concerning robotic agents, they may have zero size, instant connection capabilities or very simplified kinematics. These models are quite far from practical usage, but there is an essential need in them when even theoretical feasibility of a particular task is in a doubt.

3.3 Swarm Robotics vs. Weak Robots

There is one more term similar to robotic swarms - "weak robots". This term was used a decade ago in studies dedicated to fully theoretical researches of multiple mobile robots possibilities. Robots denoted by this term have very special characteristics [5,6], which are described as follows:

- The robots are anonymous. The members have no identity and no way to distinguish them from each other.
- The robots are autonomous. There is no any central control unit or scheduler to control robots' behavior.
- The robots are disoriented. Robots do not have any common coordinate system(s) nor a common sense of direction. In particular cases even coordinate systems handedness (or chirality) are not common [8].

– The robots are homogeneous. All robots must follow the same program.
– The robots are oblivious. Robots do not have a memory storage to store results of previous computations or observations.
– The robots are have no communication. Robots do not have any direct ways to communicate with each other.
– The robots are able to observe all other robots. All robots have the ability to observe any other robot position at any moment of time.

Such requirements are far from practical usage: it is practically impossible to have a computational unit without memory storage device (at least, RAM) or positioning system with a capability to observe multiple robots positions accurately. This model was useful for theoretical estimation of robots possibilities in such strong limitations. However, due to the problems with practical implementations a concept of weak robots is not popular. While collecting the material for this paper, we noticed that this term was not used in new robotic studies for more than five years.

4 Discussion

The terms that were reviewed in the previous sections are easy to confuse with each other and they should be used carefully. Therefore, researchers pay a lot of attention to terminology used and there are multiple examples of proper terms usage.

Multi-agent systems term - is the most conservative way to denote a group of robots without a risk to identify a studied system type incorrectly. In addition, the principles that are designed for multi-agent systems generally could be used for non-robotic systems. For example, methods that were proposed for formation tracking [13], formation producing [9], formation control [29], and multi-agent tasks reviews - they stay actual for any system with multiple entities with desired properties (sensing and communication capabilities, kinematics, etc.). Such definition includes groups of people, flocks of birds and animal packs. Therefore, the more generic is the model being used, the higher is a chance for the system to be referred as a multi-agent. This determines MAS term usage in mostly theoretical studies, e.g., [9,20].

Multi-robot systems term is a narrower term, which is used in more practical cases, when proposed methods or algorithms are designed especially for using with robotic system, considering real robot limitations and properties, for example, a robot size, sensors' noise and reliability, communication bandwidth and instability, etc. Typically, they are tested in experiments to practically prove particular advantages of proposed methods. Experiment results in such cases become the most important part of the study, allowing to understand the significance of the research: an accuracy reached [16], an observed failure rate [15] and other properties. Swarm robotics is only a part of multi-robot systems and it is easy to distinguish between them, using definitions that we have given above. Therefore, using the definitions, it is easy to verify, that a system studied in [18] is a multi-robot system, but is not a swarm, as it was explicitly denoted in the research: robots used in the study are not identical and anonymous, there is a leader to follow and every robot can distinguish its neighbors from each other.

Swarm robotics has a very narrow and precise definition; therefore, researchers should pay attention to its usage. For example, a swarm that was proposed in [21] cannot be referred as a swarm because it uses specially selected "seed robots" for creating a coordinate system. In addition, there is a subtle difference with sensor networks, as it is shown in the example of [14], where a robotic swarm changes its form sensor network after deployment within an operating site. Additional examples of robotic swarms could be found in multiple forms: methods that include complex interactions [12], or on the opposite very simple stochastic systems [17] and bioinspired systems that directly transfer natural behavior onto robotic systems [10].

5 Conclusions

Swarm robotics is a fast-growing area of robotics. Researchers around the world propose new methods to increase localization accuracy, movement control stability, collaboration effectiveness etc. All the previously constructed foundation is used to find solutions of complicated tasks, including effective environment exploration, formation control, data transmission, while practical solutions are developing at the same time. As studies count increases, the terminology requires a revision in order to provide a proper level of unification and precision - even a unique "swarm robotics" term needs to be established. Since there are multiple types of collective robotics approaches and corresponding methodology, swarm robotics field terminology must be explicitly distinguished from others.

In this paper, we reviewed and refined definitions that had been proposed in previous researches of robotics field. We demonstrated relations between swarm robotics and concepts of adjacent fields including multi-agent systems, multi-robot systems and sensor networks. We believe that our attempt to contribute toward unification of swarm robotics terminology and classification succeeded to clarify distinctions between the terms that are often mistakenly used as pure synonyms.

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