From Swarm Intelligence to Swarm Robotics

Gerardo Beni

Department of Electrical Engineering,
University of California, Riverside CA 92521, USA
beni@ee.ucr.edu

Abstract. The term “swarm” has been applied to many systems (in biology, engineering, computation, etc.) as they have some of the qualities that the English-language term “swarm” denotes. With the growth of the various area of “swarm” research, the “swarm” terminology has become somewhat confusing. In this paper, we reflect on this terminology to help clarify its association with various robotic concepts.

1 Introduction

This paper is meant as an introduction to a panel discussion on the use of various terms in current use, such as “swarm”, “swarming”, “swarm intelligence”, “swarm optimization”, “swarm engineering” and “swarm robotics”. I will try to give some perspective by way of tracing, very imperfectly and subjectively, the evolution of some of these terms, hoping that, in looking at them, some robotics concepts may become clearer.

2 Why “Swarms”

About 20 years ago there was a significant interest in cellular automata; the interest diminished in the nineties until recently when the new book by Wolfram was published [1]. Wolfram gave some of the most important contributions to cellular automata theory in the early eighties. At that time, being interested in the topic of self-reproducing robots, I became interested in cellular automata since they can produce patterns of significant complexity starting from simple rules. Around the same time, Fukuda in Japan used the term “cellular robots” [2] to indicate groups of robots that could work like cells of an organism to assemble more complex parts. I used also the term “cellular robot” [3] but to indicate an extension, or a more general type, of cellular automaton. The extension was simply the fact that the units of the automaton were not operating synchronously nor sequentially and were moving and interacting dynamically. They were meant to represent a group of simple robots, self-organizing in new patterns.

With Jing Wang, we presented a short paper on cellular robots at one of the Il Ciocco conferences [4]. The discussion was quite lively and I remember Alex Meystel saying that “cellular robot” was an interesting concept, but the name was not appealing; a buzz word was needed to describe “that sort of ‘swarm’ ”, as he put it. I agreed that the term “cellular robot” was not very

E. Şahin and W.M. Spears (Eds.): Swarm Robotics WS 2004, LNCS 3342, pp. 1–9, 2005.

exciting and, besides, it had already been used by Fukuda. By the way, also the term "cellular automaton" is probably not a very good choice. (May be part of the reason more people have not pursued that field is that it did not have a good buzz word.) Anyway, in thinking of how to call the "cellular robots" with a better term, I did not make any leap of imagination but simply used the word "swarm" that Alex had mentioned casually. There were some good reasons though. The fact is that the group of robots we were dealing with was not just a "group". It had some special characteristics, which in fact are found in swarms of insects, i.e., decentralized control, lack of synchronicity, simple and (quasi) identical members. Important was also the size, i.e., the number of units. It was not as large as to be dealt with statistical averages, not as small as to be dealt with as a few-body problem. The number of units was thought to be realistically of the order of $10^2 - 10^{<<23}$. So "swarm" was not just a buzz word but a term quite appropriate to distinguish that type of group.

Swarms were appealing as robotic systems since, compared to centralized systems designed for the same task, they had very simple components. Thus, the robotic units could be, in principle, modularized, mass produced, and could be interchangeable and maybe disposable. The second main (promised) advantage was reliability: since the swarm was in general highly redundant, the swarm could be designed to survive through many kinds of disturbances (possibly more severe than those considered in standard control systems); because of redundance, the swarm would have the ability to adapt dynamically to the working environment– another feature required for high reliability. It was also possible to envision the swarm as acting like a massive parallel computational system and thus carry out tasks beyond those possible to other type of robotic systems, either complex single robots or centralized groups of robots. (This is the main topic of section 4.)

While the swarm appeared as a very promising concept for robotics, Guy Theraulaz came to visit with us for a while and spoke about his work with insects [5]. It was clear that the concept of swarm was quite appropriate for insect societies. While roboticists tried to make the swarm do some prescribed tasks, the biologists tried to explain the behavior of insect societies as swarms. All the key qualities of swarms apply to insect societies: decentralized, not-synchronized, with quasi-homogeneous, simple units, not in "Avogadro-large" numbers. A key concept in their model of swarm was "stigmergy", i.e., communication by way of the environment. Ants communicate to other ants the "quality" of a path by marking it with pheromones so that a positive feedback mechanism ends eventually in most insects following the "best" path. This is an example of "swarm optimization", and in this particular area the concept of swarm has been most successful.

3 Why "Swarm Optimization"

While progress by roboticists in making swarms of robots do prescribed tasks has proceeded slowly, progress by biologists and other interested in optimization has been significant. It also seems entirely appropriate to use terms like "swarm optimization" to include algorithm such as Dorigo's [6] "Ant Colony Optimization" (ACO) algorithm and the "Particle Swarm Optimization" algorithm of Kennedy and Eberhart [7]. The word "swarm" here is appropriate because the algorithms are run asynchronously and in a decentralized fashion. They also mimic the stigmergic behavior of swarms of insects. This aspect of what swarms can do has been original to biologists and was not considered extensively by roboticists. The main departure is in the goal of the swarm. Roboticists were looking at the swarm as a constructor, a system to create patterns or some kind of ordered structures either internally, as self organization, or externally, as, e.g., self reproduction. Biologists instead were also looking at the swarm as a pattern analyzer, a system capable of recognizing the best way to do something. From this perspective the applications to stochastic optimization followed. Actually, besides foraging and related optimization problems, biologists were also looking at swarms of insects as creators of patterns since, e.g., in termite societies, swarms of termites build complex structures. The interest was in modeling how the swarm can build ordered complexity [8].

Looking at these various perspectives, it is not surprising if the concept of swarm appears more and more to be closely associated with systems capable of carrying out not just useful tasks but also "intelligent" tasks. From the robotic side, swarms self-organize into patterns. From the biological side they construct ordered patterns. The production of ordered patterns is a characteristic of intelligence. (Of course this is extremely simplified; in practice, robots can also manipulate objects and construct patterns, not just move around). Another is the recognition and/or analysis of patterns, which swarms do when they optimize a function. So, from all sides, we are led to look at the swarms as maybe doing something intelligent – "swarm intelligence".

4 Why "Swarm Intelligence"

"Swarm" and "swarm optimization" are appropriate terms to represent two well-defined concepts. The term "Swarm Intelligence" is more complicated to justify mainly because the term "intelligence" is very difficult to deal with [9–11]. A similar situation applies in Artificial Intelligence. As is well known, there is no satisfactory definition of intelligence. The concept is elusive. There are many qualities of intelligence, but, for any one of them, one can think of some non-intelligent system that has it. Dealing with robotics, we wanted to restrict the attention to some qualities of intelligence relevant to robotics.

One characteristic of intelligent behavior is the production of something ordered, i.e., unlikely to occur: an improbable outcome. Another is the fact that this outcome should not be predictable. A manufacturing machine produces a mechanical piece (ordered pattern, improbable outcome) but in a predictable way. We do not consider that machine intelligent. On the other hand the designer that produces the design of that mechanical piece is considered intelligent. Nobody knew what the designer would come up with. She was unpredictable. But of course just unpredictability is not intelligence; a roulette is not intelligent. It seems that somehow both unpredictability and the creation of some order are necessary to be able to speak of "intelligence".

In [12], we were thinking about this concept of intelligence in relation to the cellular robots and ended up calling it "swarm intelligence" (with no pretense of knowing what intelligence is). To get to that definition, in [12] we labored through a set of preliminary definitions, as follows.

Machine: an entity capable of mechanical behavior, i.e., of transferring and/or processing matter/energy.

Automaton: an entity capable of informational behavior, i.e., of transferring and/or processing information.

Robot: a mechanical automaton, i.e., an entity capable of both mechanical and informational behavior.

These three definitions are somewhat different from those in common usage but they help avoiding confusion since they contain only the two well-defined concepts of matter/energy and information. Strictly speaking, a "pure" machine cannot exist. A machine is always also an automaton since mechanical states contain information; in processing/transferring matter, a machine always also processes/transfers information (In contrast, an automaton can be a pure automaton since it operates on representations of states, not on physical states). Thus, in the definition of machine given above, there is the implied assumption that the information change is negligible with respect to the mechanical change produced by the machine.

An intelligent robot was defined as,

Intelligent robot (preliminary def. 1): a robot whose behavior (as defined below) is neither random nor predictable (as specified below).

Note that all the previous definitions apply to a generic entity regardless of its plurality, so they apply to groups of units as well. Groups of automata cannot be robots since they do not process matter/energy. But groups of pure (as defined above) machines can be robots since they can process information by changing mechanical states (e.g., by encoding information in patterns of the group). Thus intelligent robots can be built out of groups of pure machines. At this point the possibility of an intelligent robot made from a group of non-intelligent ones has been defined. However, the definition of intelligent robot still needs specifications. First, about "behavior", it is necessary to define the intelligent robot's behavior in terms of its relation to patterns of matter, i.e., arrangements of material objects, in contrast to arrangements of representations. In terms of patterns, there are two types of intelligent behavior: pattern analysis and pattern synthesis. The former can be accomplished by an automaton, the latter only by intelligent robots. Thus, the behavior specific to the intelligent robot was defined as the synthesis of material patterns. Thus,

Intelligent robot (preliminary def. 2): a robot capable of forming material patterns unpredictably (in the sense specified below).

At this point in [12] the concept of intelligent swarm could be formulated as:

Intelligent swarm (preliminary def. 3): a group of non-intelligent robots forming, as a group, an intelligent robot. In other words, a group of "machines" capable of forming "ordered" material patterns "unpredictably".

Note, in passing, that the swarm algorithms derived from foraging, such as the ACO algorithm and the PSO, are forms of pattern analysis behavior. The swarm finds an optimal pattern (e.g., path, function, etc.). Thus, the systems described by these algorithms are more swarm automata than swarm robots. On the other hand the termites' behavior in building structure is characteristic of the intelligent robot behavior defined above.

Most of the rest of [12] was a discussion of "unpredictability". Without a clear notion of unpredictability, the definition of intelligent swarm could be applied to trivial systems. For example, the definition could be satisfied by a mechanical "screen saver" that produces interesting patterns from a random algorithm. But picking at random some ordered patterns from a set is not the idea of unpredictability that suggests intelligence. Thus, anything that appears unpredictable simply because it is not accessible must be ruled out. Eventually the argument for unpredictability runs into the computational power of the system which is very appropriate, since the concept of intelligence has been often associated with computational power, as the Turing test, chess playing computers, and other AI arguments show. At this point we could further improve the definition of Intelligent Swarm as,

Intelligent swarm (preliminary def. 4): a group of "machines" capable of "unpredictable" material computation.

Unpredictability can be achieved if the system making the prediction is not capable of outrunning the system it is trying to predict. Now, if a system is capable of universal computation it cannot be outrun. In fact if one tries to predict a system which is capable of universal computation, one must use another universal automaton to simulate the first. Thus, the infinite time behavior of a system capable of universal computation is in general unknowable in any finite time: the problem is formally undecidable.

Our interest though was not so much in a system that is unpredictable at infinity, but at every step, or at least over a finite range of time; so, undecidability was not an entirely satisfactory choice for "unpredictability". We were looking for a system (the intelligent swarm) which cannot be predicted in the time it takes to form a new material pattern (of its own components). The issue is more one of tractability than decidability.

Normally one does not have a way of telling whether the method used for a particular computation is the most efficient possible. No clear lower bounds on the difficulty of computation have ever been established. The rate of computation is the issue. In general, once you have a system that is universal, you can make it to do any computation but the rate at which the computation is done is not obvious. In fact, without special optimization, a universal Turing machine will typically operate at some fixed fraction of the speed of any specific Turing machine that it is set up to emulate. Indeed, a priori, there can be great differences in the rates at which given computations can be done. However, it turns out [1] that a large number of universal systems can be made to emulate each other in a comparable number of steps. So, can a swarm be outrun? Certainly if is not properly designed. However, it is very plausible that the swarm can be designed so that no system capable of universal computation can outrun it. This is easy to see in the case of a Von Neumann architecture universal automaton versus a swarm.

To form the new pattern the intelligent swarm S would need to do (1) computations and (2) motions. The swarm does (1) and (2) in parallel. A universal automaton A trying to predict S must do (1) and simulate (2). We may assume that for S the time T_2 for (2) is much larger than for (1); but it is independent of N, the number of units in S, since the motions of the units may be assumed to occur in parallel. If A has a Von Neumann architecture the computation time scales with the number of states to be dealt with. If N is large enough this time will exceed T_2. So an automaton with von Neumann architecture could not predict the outcome of the intelligent swarm.

A more serious challenge to the intelligent swarm comes if A has a cellular automaton architecture and it is set up to simulate the intelligent swarm from its initial state. However, also in this case, A may not be able to outrun the swarm. The key is of course that the swarm be designed so as to be capable of universal computation. This is quite feasible since it has now become clear [1] that relatively simple (in terms of rules of evolution) systems are capable of universal computation. And swarms are actually generalization of cellular automata so there is no conceptual difficulty in thinking of a swarm capable of universal computation. The second key point is that in general, given a universal automaton, it is quite feasible to design it so that it cannot be outrun. This happens if, given a particular initial condition, an irreducible amount of computational work is required to find the outcome after a given number of steps of evolution. It is now considered likely that, asking about the possible outcome after a certain finite number s of steps of evolution of a universal system is a NP-complete problem. In other words, no Von Neumann or cellular automaton will ever be able to guarantee to solve this problem in a number of steps that grows only like some power of s.

So the intelligent swarm is unpredictable in the sense that it can be constructed as a computationally intractable system. Thus, the definition of intelligent swarm can be further refined as,

Intelligent swarm: a group of non-intelligent robots ("machines") capable of universal material computation.

Basically, the intelligent swarm [12], in terms of its unpredictability, is a particular instance of the principle of computational equivalence (and the concept of computational irreducibility) which Wolfram discovered in the '80s while working on cellular automata [13]. After the publication of [1], these concepts are becoming much clearer and more widespread. Which has further consequences for swarms. In fact, it now appears quite plausible that swarm intelligence is not just an interesting concept but something quite likely to be found in nature and quite feasible to engineer.

The whole point of defining the intelligent swarm was that one felt reassured of not studying a trivial system or a system that could easily be mapped into other well known systems. Swarm intelligence was an emergent property which led to systems of significant power in forming patterns of matter. The intelligent swarm could be a universal mechanical computer and as such unpredictable. It also showed that swarms were not just capable of doing what single robots do, but more capable. Thus, e.g., for defense applications, the swarm was inherently more promising (for this and other advantages) than the single robot, and, arguably, still is.

5 Why "Swarm Robotics"

The term swarm intelligence became more and more in use during the last 15 years and, as we have noted in sect. 2 and 3, generally with good justification. At the same time, the original application of the term (to robotic systems, sect. 4) did not grow as fast. One of the reasons is that the swarm intelligent robot is really a very advanced machine and the realization of such a system is a distant goal (but still a good research and engineering problem.) Meanwhile, it is already very difficult to make small groups of robots do something useful. Thus, there is not much reason to use a term (swarm intelligence) for much more modest groups of robots. It seems reasonable that terms such as "collective" robotics and "distributed autonomous robotic systems" should be used.

On the other hand, the use of labels such as "swarm robotics" or "collective robotics/distributed robotics" should not be in principle a function of the number of units used in the system. The principles underlying the multi-robot system coordination are the essential factor. The control architectures relevant to swarms are scalable, from a few units to thousands or million of units, since they base their coordination on local interactions and self-organization. The fact that only small groups of robots have been presented in most of the swarm robotics literature is a side effect of cost of robotic equipment and of the number of technologies involved to make robots working. Making a single mobile, autonomous robot working in a reliable way is already a big challenge nowadays, and even more so for a robotic swarm.

In biology, there is no such a mismatch between the term "swarm" and the systems one is looking at. First, because "swarm" is obviously the English-language word that describes some of the biological systems studied, regardless of whether or not what they do is intelligent. Second, because "swarm" is intuitively applicable to relatively large random systems that do something interesting. For example, "swarming" is used to describe mathematical solutions to some high order PDE [14]. Here it is clear that the term has a more distant relation to the concept of swarm as originally appeared in robotics (sect. 2); nevertheless it is a reasonable English language description when one looks at the patterns formed by the solutions of those PDEs, which resemble the paths of swarming fish or birds.

Swarm robotics [15], as a discipline, has attracted a significant number of research groups currently contributing to the field. An incomplete list of such groups includes: Caltech, Carnegie Mellon, Ecole Polytechnique Lausanne, Georgia Tech, Hughes Research Labs, MIT, Middle East Technical University, Riken, Texas A & M, Tokyo Institute of Technology, University of Alberta, UCLA, Universitat Karlsruhe, Université Libre de Bruxelles, USC, University of West England, University of Wyoming, Washington University.

Looking at applications, swarm robotics has by now accumulated a collection of "standard" problems which recur often in the literature. (This workshop itself describes a large array of such problems.) One group of problems is based on pattern formation: aggregation, self-organization into a lattice, deployment of distributed antennas or distributed arrays of sensors, covering of areas, mapping of the environment, deployment of maps, creation of gradients etc. A second group of problems focuses on some specific entity in the environment: goal searching, homing, finding the source of a chemical plume, foraging, prey retrieval, etc. And another group of problems deals with more complex group behavior: cooperative transport, mining (stick picking), shepherding, flocking, containment of oil spills, etc. This, of course, is not an exhaustive list; other generic robotic tasks, such as obstacle avoidance and all terrain navigation, apply to swarms as well.

Another aspect of swarm robotics that should be mentioned is "swarm control". Ultimately, after algorithms for task implementation have been devised, the practical realization requires robustness and this is the result of proper control. Swarm control presents new challenges to robotics engineers. The closest classic example, from the control engineering side, is perhaps formation control, e.g., the control of multi-robot teams or autonomous aircrafts or water vehicles. These studies lead to consider problems of asynchronous stability of distributed systems and are very much in line with the original drive toward swarm robotics. A brief review of these problems, as well as their relation to swarming in general, is given in the introduction section of a recent paper by Passino [16] whose work has focused on swarm robotics control.

In thinking about the actual realizations of swarms, it is important to mention also the new term "Swarm Engineering" coined by Alan Winfield and discussed in this workshop [17]. The notion goes beyond the control concepts of robustness and adaptation and brings about the issue of dependability in the actual realization of practical swarms. Generally, looking at swarm robotics and swarm engineering in a long range perspective, we may regard these notions as guiding paradigms toward the practical realization of systems capable of swarm intelligence as discussed in the previous section.

Overall, for the roboticist interested in engineering robotics swarms, all this nomenclature using the term "swarm" maybe a bit frustrating especially when trying to organize conferences to discuss swarm robotics problems. So, although defining terms is not one of the most creative activities, there is some valid justification in trying to describe more clearly the field of "swarm robotics". What is happening is a normal process of differentiation as fields grow. The success of the term "swarm" in various branches of science and technology is creating some confusion in understanding what type of swarm one is talking about; and so the need to separate various swarm areas has probably come. At the same time, looking at swarms themselves, we see that confusion (randomness) is an intrinsic reason for their power to do remarkable tasks. So, if at this time there is some confusion among swarm researchers, it may turn out to be a good thing.

Acknowledgement

The author thanks the referees for criticism and for many valid comments and suggestions, especially pertaining to the literature cited and the concept of intelligence and swarm robotics. The second paragraph of section 5 is taken almost verbatim from a referee's comment.

References

1. Wolfram, S. "A New Kind of Science", Wolfram Media (2002)
2. Fukuda, T., Nakagawa, S. "Approach to the Dynamically Reconfigurable Robotic System", Journal of Intelligent Robotic Systems, 1, (1988) 55–72
3. Beni, G., "The Concept of Cellular Robotic Systems", Proc. 3rd IEEE Int'l Symp. Intelligent Control, Arlington, VA, August 24–26 (1988) 57–62
4. Beni, G., Wang J., "Self Organizing Sensory Systems," in "Highly Redundant Sensing in Robotic Systems", Tou, J.T., Balchen, J. G., eds., Proc. of NATO Advanced Workshop on Highly Redundant Sensing in Robotic Systems, Il Ciocco, Italy (June 1988), Springer-Verlag, Berlin (1990) 251–262
5. Theraulaz, G., Pratte, M., Gervet, J., "Behavioural profiles in Polistes dominulus Christ wasp societies : a quantitative study", Behaviour, 113 (1990) 223–250
6. Colorni, A., Dorigo, M., Maniezzo, V., "Distributed Optimization by Ant Colonies", Proc. 1st European Conference on Artificial Life, 1992, 134–142
7. Kennedy, J., Eberhart, R.C., "Particle Swarm Optimization", in Proc. IEEE Int'l Conference on Neural Networks, 4 (Perth, Australia) 1995, 1942–1948
8. Theraulaz, G., Bonabeau, E., "Coordination in distributed building". Science, 269(4):686–688, (1995)
9. Parrish, J.K., Hamner, W.M., Eds., Animal Groups in Three Dimensions. Cambridge,U.K.: Cambridge University Press, 1997
10. Camazine, S., Deneubourg, J-L., Franks, N. R., Sneyd, J., Theraulaz, G., Bonabeau, E., Self-Organization in Biological Systems. Princeton, NJ: Princeton Univ. Press, 2001
11. Bonabeau E., Dorigo, M., and Theraulaz, G., "Swarm Intelligence: from natural to artificial systems", New York, NY. Oxford University Press (1999)
12. Beni, G., Wang, J., "Swarm Intelligence in Cellular Robotic Systems", Proceed. NATO Advanced Workshop on Robots and Biological Systems, Tuscany, Italy, Jun. 26–30 (1989)
13. Wolfram, S. "Undecidability and Intractability in Theoretical Physics", Physical Review Letters 54 (1985) 735–738
14. Topaz, C. M., Bertozzi, A. L., "Swarming patterns in a two-dimensional kinematic model for biological groups", SIAM J. Appl. Math., to appear (2004)
15. Dorigo, M., Şahin, E., "Swarm Robotics– special issue editorial", Autonomous Robots, 17 (2004) 2–3
16. Gazi, V., Passino, K. M., "Stability Analysis of Social Foraging Swarms", IEEE Trans.Syst. Man and Cybern -B 34 (2004) 539–557
17. Winfield, A.F.T., Harper, C.J., and Nembrini J., "Towards Dependable Swarms and a New Discipline of Swarm Engineering". In Şahin, E., Spears, W., eds.: Swarm Robotics: State-of-the-art Survey. Lecture Notes in Computer Science 3342, Springer-Verlag (2005) 126–142