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*Review*

# Merging the fields of swarm robotics and new media: Perceiving swarm robotics as new media

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**Abstract:** The aim of this paper is to provide evidence that swarm robotic systems can be perceived as new media objects. A thorough description of the five principles of new media proposed by Lev Manovich in "The Language of New Media" is presented. This is complemented by a state of the art on swarm robotics with an in-depth comparison of the characteristics of both fields. Also presented are examples of swarm robotics used in new media installations in order to illustrate the cutting-edge applications of robotics and artificial intelligence achieved through the unity of both fields. The hypothesis of this research is that a novel point of view would be introduced by examining the field of swarm robotics through the scope of new media, which would benefit the work of both new media and swarm robotic researchers.

**Keywords:** new media object, swarm robotics, principles of Manovich

## INTRODUCTION

There have been many debates on the nature of *new media*. However, there is a famous notion saying that 'medium is the message' and it is only natural that this expression emerges from a pioneering study of new media theory by Marshall McLuhan in his revolutionary work, "Understanding Media: The Extensions of Man" [1]. Just like the book, the current paper focuses on the media itself and not the content it carries. To observe *swarm robotics* from a media point of view would be indeed a very curious case and a supplement to robotics researchers [2]. Moreover, the notion that swarm robotics can be perceived as new media objects significantly increases the field's potential for application. For example, swarm robotics could be used as an artistic tool for the creation of interactive installations. The importance of this is that the increase of applicability raises new challenges to the scientists and designers, the solution to which could be found in more scientific scenarios such as search and rescue missions.

Undoubtedly, media in its most basic form is created to be an extension of man [1]. Although swarm robotic systems do not have content like the one found in newspapers or television, they are a strong medium with significant sociological influence [3]. In their basics, swarm robotic systems are designed to be an extension of man, enabling him to explore areas that would be inaccessible to a human being. In addition to that, swarm robotic systems also assist or replace people in search and rescue scenarios that would be too hard or too dangerous to be executed by humans alone.

According to McLuhan, any medium 'amplifies or accelerates existing processes' and introduces 'a change of scale or pace or shape or pattern into human association, affairs and action', resulting in 'psychic and social consequences' [1]. With the rapid advances and the pioneering research done in the field of swarm robotics such as enabling an unanimated robot to possess processes embedded in the nature of living beings (i.e. self-regeneration and self-replication), swarm robotics amplify the existing processes of creating machines at a human concept level. This significantly accelerates the scientific advances and brings humanity to a new level of human-machine interaction [4]. Supporting this, one of the main beliefs of McLuhan about the role of media is that it continually shapes and reshapes the way in which individuals, societies and cultures perceive and understand the world [1]. This complies with advances in the field of swarm robotics that continually shape and reshape the way individuals, societies and cultures perceive the notion of robotics and their capabilities [5].

Having stated that, there can be no doubt that swarm robotic systems comply with the definition of media objects as presented by McLuhan [1]. Furthermore, it turns out that there are also a variety of principles describing the nature of new media that also hold true when it comes to swarm robotic systems. This paper presents the five main principles of new media introduced by Lev Manovich in "The Language of New Media" [6] that also apply to swarm robotics, thus proving that swarm robotic systems can be perceived as new media objects and building the bridge between the two fields of new media and swarm robotics. The hypothesis of this research is that through the analysis of swarm robotics as new media objects, a novel point of view for both roboticists and media designers can be achieved. Hence a collaboration could be formed leading to the development of more advanced technology both in the fields of new media and robotics.

## SWARM ROBOTICS AS NEW MEDIA

This section reviews the current state of the art on swarm robotics while providing a close analogy to new media objects according to the five principles of Manovich [6].

### Numerical Representation

The first and most distinctive characteristic of a *new media object* is that it is a numerical representation or, in other words, it is composed of a binary code. This brings up two key consequences. First of all, it makes the new media object *programmable*; that is to say, it can be formally (mathematically) described and is subject to algorithmic manipulation. In other words, the behaviour of the object is defined by mathematical functions in binary code. Secondly, unlike the continuous nature of analogue media, new media is *digitised*; that is to say, it is composed of discrete samples. The process of digitisation is divided into two parts. The first is called sampling. It describes the division of a new media object into separate measurements which are made according to a specific procedure [6]. The second is called quantisation. Each sample is then quantified, i.e. assigned a specific value from a predefined range. In addition, because a new media object is constructed from autonomous samples, new media is developed towards an individual customisation rather than mass standardisation. All of the aforementioned information holds true when it comes to swarm robotics.

The driving force behind the behaviour of any robot, either the most advanced industrial models or the simplistic ones used in swarm applications, is controlled by digital code. Although coding has become more accessible and visual due to the ever-increasing robotics community and the user-friendly graphical user interfaces [7], those are compiled in executable machine codes, i.e. sequences of zeros and ones. For instance, some robotic agents with a certain degree of autonomy, related also to the 2nd law of modularity and the 3rd law of automation in new media by Manovich [6], are able to self-reconfigure or self-repair by executing a set of mathematical models defined by code [8]. Therefore, the behaviour and, in certain cases, the creation of a robotic agent may be formally (i.e. mathematically) defined. This makes it possible to describe the task to be executed the way it is supposed to be executed and also the further conditions related to it (Figure 1).

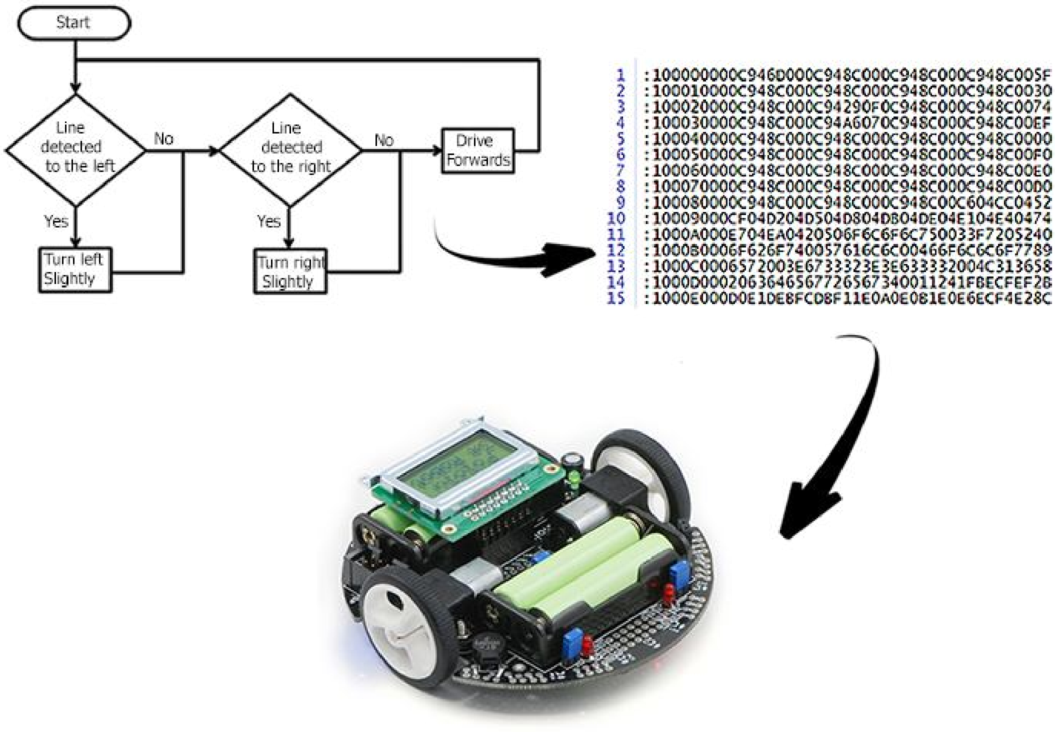



**Figure 1.** Numerical representation principle: visual representation of the behaviour of a 3pi robot in a simple line-following task, illustrating the algorithm, its compiled form and the 3pi robot itself [9-11]

As a natural consequence, the behaviour of one robotic agent or even the multi-robot system (e.g. swarm of robots) is subject to algorithmic manipulation. In other words, each robot's actions depend on the implemented processes that usually follow a given flow. Although the adaptive behaviour towards contextual information has been successfully implemented in most of the recent robotic applications [12], robots continue to follow a certain set of programmed rules, either deterministic or stochastic, algorithmically translated through coding [13].

The individual agents of a system are defined as *nodes* and can be perceived as the 'samples' constructing a new media object, given that the object itself is represented as the swarm. It is only natural that they also need to be 'quantified' with a specific identification, which would ease the communication between different agents and help to define the individual contribution to the collective behaviour of the entire swarm [14].

In short, similar to the creation of a new media object, a swarm of robots is comprised of discrete samples that are represented by autonomous agents, quantified according to their identification, whose behaviour is formally (i.e. mathematically) described and subject to algorithmic manipulation.

**Modularity**

The second principle of new media, according to Manovich, describes the structure of a new media object [6]. Modularity, or the so-called *fractal-structure* of new media, describes the specific alignment of identic elements with different scalability constructing a new media object. In other words, a new media object consists of collections of discrete samples, which can then be assembled into larger-scale ones, although they would still retain their separate identities. Again, the newly founded objects can be combined to create even larger objects without losing their autonomy. Since each object retains its independence and identity, it can be accessed and modified at any time without affecting the structure of the entire larger-scale object. Furthermore, if a specific module in the system is modified or removed, this would not jeopardise its existence as a whole. In short, a new media object consists of small and self-sufficient modules which, in turn, consist of even smaller and self-sufficient modules, thus providing the possibility of modifying one module without affecting the structure of the entire object as a whole.

This is a recurrent principle observed in swarm robotics. At the lowest level, each swarm robot comprises of multiple electronic circuits. As the work of Dorigo et al. [15] depicts, the notion of electronic modularity may be applied at that level. This is obtained by partitioning the required functionality of each module to make them as autonomous as possible.

Moving up in the hierarchy, a swarm of mobile robots consists of small, self-sufficient mobile agents that correspond to the concept of discrete samples in new media as previously mentioned. This means that each swarm and, in turn, each separate agent can be easily taken apart and reassembled into different configurations corresponding to the specific tasks of each mission. In swarm robotics, the modular structure allows for better flexibility in construction and data flow. In addition, the modular structure of the agents forming a swarm makes it possible to have different types of specialised robots in the system, thus making it more cost efficient and also increasing the separation of identity of the agents in it. A robotic swarm system usually consists of relatively few homogenous groups of robots [3]. This improves the fault-tolerance of the system; should one agent experience a failure, the execution of the task would not be severely jeopardised. Similarly, in new media if some of the samples constructing the object are damaged or missing (e.g. pixels in a digital image), the structure of the object would still be recognisable.

On a larger scale, modularity can be perceived in one more specific case of swarm robotics. This is the case where a swarm consists of several other swarms, each in turn consisting of different types of specialised agents. For example, the work of Navarro-Serment et al. [16] illustrates a use of this particular case with their example of creating a swarm combining several other swarms, each separately consisting of large all-terrain vehicles, medium-sized tank-like robots, and centimeter-scale *Millibots*. All of the swarms are designed to execute a specific task (i.e. the all-terrain vehicles being used to deploy medium-sized tank-like robots and the Milibots) and by being individual, self-sufficient parts of a swarm entity, they perfectly illustrate the modularity principle in new media. This concept is also supported in the work of Alunni et al. [14], where the author presented the idea that groups of nearby robots could self-organise to form collective agents. The hierarchy is created by the expansion of those groups of collective agents to eventually consist of the entire swarm. Similarly, Couceiro et al. [17] proposed an algorithm denoted as robotic Darwinian particle swarm optimisation, in which each swarm of robots competes to strive for a better solution while robots within each swarm co-operate. With this co-opetitive (i.e. co-operative and competitive) behaviour associated with the Darwinian principles of survival of the fittest, the swarms that are able to improve proliferate over the others and at some point all robots form a unique swarm (Figure 2a).

a)

b)

**Figure 2.** Modularity principle: a) co-opetitive behaviour with different colours representing different swarms of robots that evolve based on survival-of-the-fittest principles [17]; b) swarm of self-assembly modular robots that can reshape into a larger collective system [18]

At a higher level, the work of Wei et al. [18] (Figure 2b) discusses the use of self-assembly modular robots as a new concept in swarm robotics co-operation. As a swarm of robots use numerous simple robots to achieve the desired task through co-operation, self-reconfigurable modular robots rely on the same concept by connecting and disconnecting autonomous agents in a bigger system that can reshape, without human intervention, to adjust to the demands of the environment and the task at hand. In this case the modules relating to the idea of discrete samples are the autonomous agents while the object itself is the swarm robotic structure.

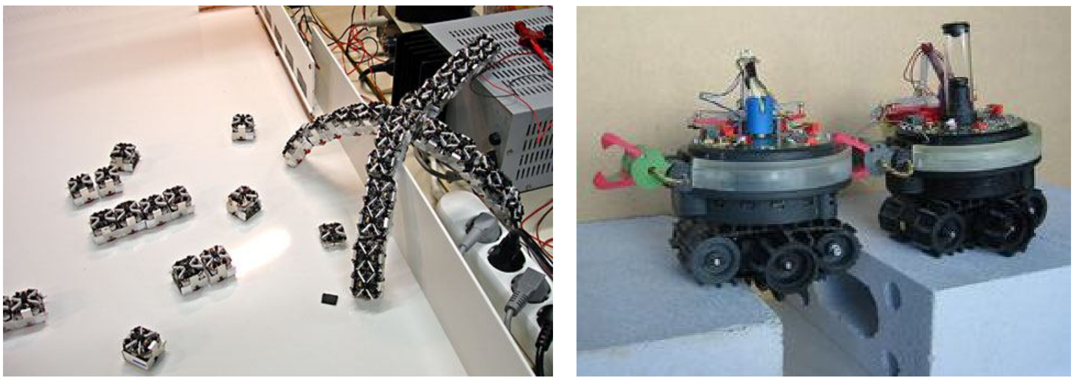
In short, the modularity design of swarm robotic systems allows for the creation of specialised robots with particular modular configuration. The combination of those simple agents forming a swarm increases its possibilities while still maintaining energy efficiency, small cost and size [16].

**Automation**

Automation is a concept inherent to both new media and swarm robotics. In new media automation is a process in the creation or modification of a certain object, which removes, at least partially, the need for human intervention. This concept becomes possible because of the existence of the aforementioned principles of numerical coding (the first principle of new media) and modularity (the second principle of new media), and it allows for parts of the modification, creation and access processes to be done without human intervention [6]. The process of automation in new media is divided into two sub-categories: low-level automation and high-level automation. The difference between the two categories is that while low-level automation processes allow the user to create new media objects using templates or simple repetitive algorithmic computations, high-level automation requires a computer to understand to an extent the semantics behind the generated objects [6].

It is in the process of high-level automation that new media most significantly resembles robotics since high-level automation is one of the approaches of artificial intelligence engines and an inseparable part of both new media and swarm robotics used to simulate bio-inspired intelligence. Ismail [19] described the latest projects in the field of swarm robotics as the so-called *Symbrion* and *Replicator* projects. Both of them were inspired by swarm intelligence based on natural examples and focused on enabling the agents in the swarm to autonomously manage their software and hardware mechanisms. This is believed to configure the robotic organism in a way that would make it self-healing, self-optimising and self-protecting against software and hardware failure. Hence a swarm would be created of exceptionally adaptive agents that would also have enhanced scalability and ability to evolve. Furthermore, it is believed that the robots forming the swarm would also have the ability to reprogramme themselves, which would significantly increase the degree of automation.

High-level automation is also considered to be related to the degree of evolvability inherent to a swarm. Similar to high-level automation in new media, in this case the swarm is required to 'think' or, in other words, to have a certain understanding of the configurations it could autonomously reshape so as to, for instance, overcome obstacles (Figure 3b). This example is thoroughly illustrated by Kernbach et al. [20]: in order to overcome an obstacle and reach the recharge station, a swarm has to 'grow legs' by forming a collective organism of a quadruped robot which would enable it to 'step over' the obstacle (Figure 3a).



a) b)

**Figure 3.** Automation principle: a) Replicator and Symbrion project agents forming a four-legged robotic structure in order to overcome the barrier to the charging doc [20]; b) similar situation in which two foot-bots dock together to overcome the lack of bridge between the two surfaces [15].

Alternatively, the work of Dai et al. [21] discusses a prototype for a self-healing and self-reproducing swarm robotic system. Their goal is to create, by using Autonomic Computing, which mimics the autonomic nervous system present in most bio-organisms, a virtual neuron which would be in charge of the monitoring of the hardware and software systems of the agent. In addition to that, it would have certain *prescriptions* embedded in its code that would take care of the analysis and reparation of possible system failure. Moreover, due to the virtual neuron, the agents in a swarm would be able to mutually heal one another or in the case of complete failure of an agent, another agent would be able to collect the good 'organs'. If a sufficient stack of organs is gathered, a third robot could autonomously combine those to make a new agent. The latter process is called *self-reproduction.* Other means of self-reproduction may involve the creation of a robot from the spare parts of other robots. The time and execution of this process is dictated by the virtual neuron and happens without human intervention, thus presenting this work as being an extreme case of high-level automation in swarm robotics.

However, low-level automation in the form of simple repetitive actions is also observed in swarm robotics. For example, the work of Melhuish et al. [22] shows how, by following four simple programmed rules (principle of numerical representation), a swarm of robots are able to perform a complicated task like carrying and sorting out several different types of objects. Such complicated patch sorting task can be achieved using a simple mechanism and without any sort of explicit communication between robots, thus making this approach highly scalable. Most of the control architectures in swarm robotics have included a low-level automation layer. For instance, many swarm robotic behaviours are programmed without considering obstacle avoidance or the kinematic or dynamic structure of robots [23]. The work of Pugh and Martinoli [24] was one of the first adapted versions of the particle swarm optimisation to handle real world constraints by using the *Braitenberg* obstacle avoidance algorithm [25]. Such low-level behaviours were subsequently programmed in swarm robots as a low-level control layer that receives the output commands of the main layer and translates those into low-level commands designed for a specific robotic system.

In short, high-level and low-level automation are present both in the field of new media and that of swarm robotics. Low-level automation is exhibited in the repetition of simple algorithmic computations used to describe the behaviour or the creation of an object while high-level automation requires a certain degree of understanding about the nature of the object that is being generated.

**Variability**

Variability in new media is closely related to the nature of new media as are numerical representation (first principle) and its modular structure (second principle). It means that a new media object can exist in different, potentially infinite, versions of itself [6]. What is specific to a new media object is that instead of simply having completely identical copies of itself, it enables the creation of many different versions. A necessary condition for the existence of variability in a new media object is the presence of modularity. The modular structure of a new media object, made of autonomous discrete samples, makes it possible to reassemble the separate modules in the object under the supervision of preprogrammed computations.

The concept of variability is also present in the field of swarm robotics. As previously mentioned, just like a new media object, a swarm has a modular structure consisting of a large number of autonomous agents which can be configured in accordance with the objectives of the task at hand [18]. The behaviour of the swarm is subject to algorithmic computations (numerical representation) and each swarm robotic system also possesses a certain degree of automation.

A specific case of the variability principle in new media is that the media elements are various and stored in a database from which they can be assembled beforehand or on demand. A similar case is illustrated in the field of swarm robotics. Calisi et al. [12] proposed that each robot of the created prototype swarm would have a certain amount of spare parts attached to its body. In the case of self-reproduction dictated by the virtual neuron, a new robot could be autonomously assembled by the others to fit the requirements of the environment. This new robot would be a perfect example of the variability principle since it would be constructed from different modules present in the swarm 'database' and its construction would be subject to predefined computations.

In terms of software, the work of Waibel et al. [13] presents a novel approach to storing the shared memory of multiple robots into a database called RoboEarth. Unlike other methods in which the vast majority of data for robots is tightly dependant on the robots' hardware and difficult to reuse across platforms, RoboEarth collects, stores and shares information in a platform-independent way, thus making it widely effective throughout various configurations and scenarios. Also, the aim of the RoboEarth project is to enable the sharing and reuse of knowledge instead of using the collected data only to create algorithms to be used offline without connection to the original information. According to the authors, the benefit of this approach would be a better coordination and improved efficiency in missions requiring the robots to operate in complex, unstructured environments. The RoboEarth database is subject to constant update since at the end of each task the robot shares the acquired knowledge by uploading it to the distributed database. This is yet another link to the variability principle in new media, which defines a new media object to be subject to constant updates [6].

Another example of the variability principle in new media is termed *hypermedia*. Manovich defines hypermedia as systems that provide the user with the ability to create, manipulate and examine a network of information containing nodes connected by relational links [6]. Hyperlinking provides the connection (i.e. the wiring) between the different nodes in the network. This is of course possible due to the modular nature of new media and the principle of numerical representation. The hypermedia example can also be found in swarm robotics. From the definition, it can be deduced that hyperlinks represent the connecting wires in a decentralised network and are in charge of the control and navigation of the entire system.

The work of Dorigo et al. [15] illustrates this principle. The authors proposed an innovative swarm robotic system built from several swarms of three types of different autonomous agents (also supporting the modularity principle) called *Swarmanoid*. The Swarmanoid consists of a sub-swarm of small autonomous agents called *foot-bots*, which specialised in movement on both even and uneven terrains (Figure 4b), and which are also capable of self-assembling and transportation. There is also a sub-swarm of *hand-bots* (Figure 4a) which are capable of manipulating small objects and climbing vertical surfaces. Finally, the Swarmanoid system also consists of a sub-swarm of autonomous flying agents called *eye-bots*, which are capable of attaching themselves to indoor ceilings, analysing the environment and transporting both the foot-bots and the hand-bots. Supporting the concepts of modularity and automation, the agents of a particular type in the swarm system are directly interchangeable and also possess self-configurability. In this particular example, the eye-bots act as navigational agents between the foot-bots and hand-bots in a decentralised system, providing the wiring link between the two subsystems.

A system with a hyperlink typology also has a branching structure and an if-case application — a certain action is executed if a certain condition is fulfilled (Figure 5a). This also applies to the behaviour of the separate agents in the work of Dorigo et al. [15]. In the Swarmanoid system for search and retrieval scenarios the environment is scanned by the eye-bots. If they detected the desired object in the environment, the location would be passed down to the foot-bots, which should bring a hand-bot to the place (since hand-bots have no ability for locomotion on their own) (Figure 5b).

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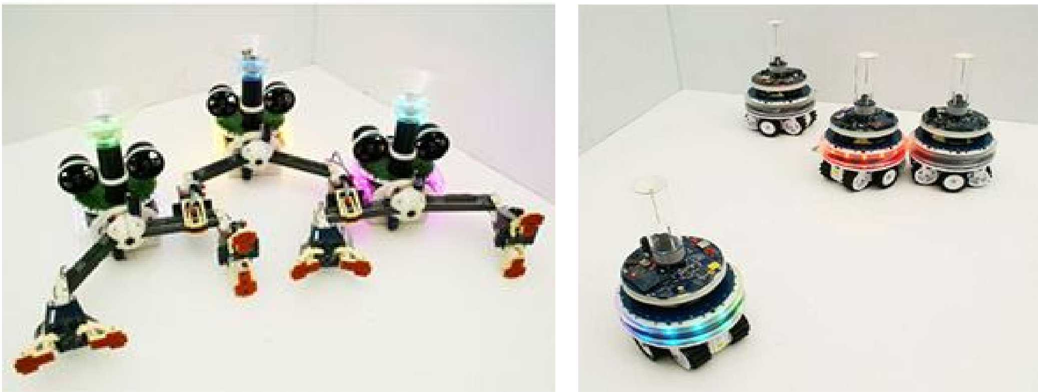
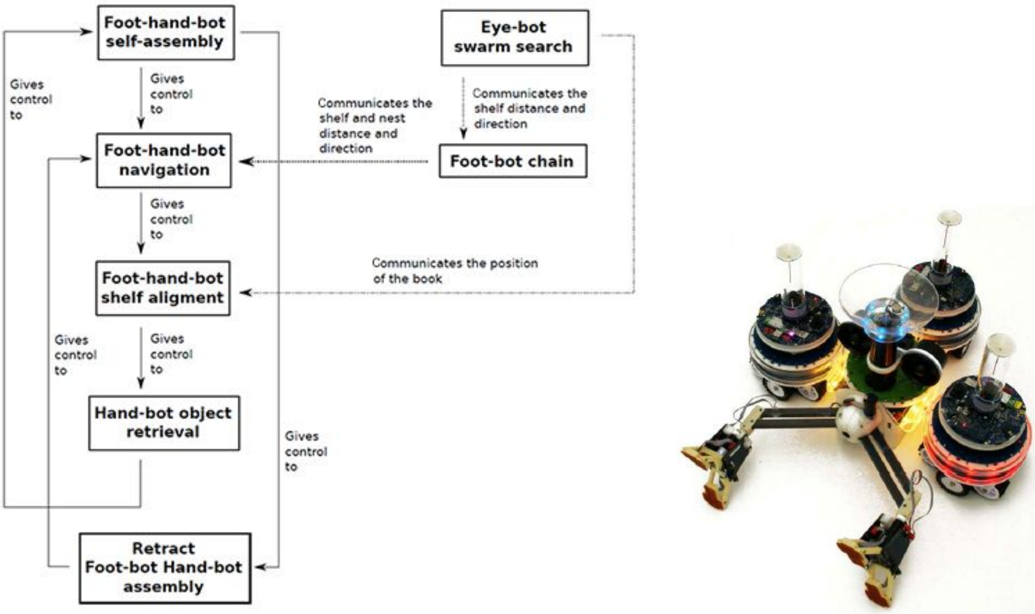


a) b)

**Figure 4.** Variability principle: a) Hand-bots, a sub-swarm of the Swarmanoid project, capable of climbing vertical surfaces and manipulating small objects [15]; b) Foot-bots, a sub-swarm of the Swarmanoid project, capable of self-assembling and transportation [15]




a) b)

**Figure 5.** Variability principle: a) a scheme representing the behavioural scenario and the interactions of the robots within the Swarmanoid [15]; b) foot-bots docked to a hand-bot in order to bring it to the desired location [15]

In the programming code defining the behaviour of a swarm robotic system, a branching topology can also be found [15]. The system is programmed to execute an action if a certain condition is true, thus creating a set of commands that aim at covering the actions for as many conditions as possible. This way it is also possible to obtain a higher degree of automation. For example, every time the swarm encounter an obstacle, they follow the predefined actions for that condition or, in other words, they execute only one version at a time from the pre-programmed code. The branching code topology defining the behaviour of a swarm robotic system serves as a definite example of how the principle of variability applies to swarm robotics.

Another sub-case of the variability principle in new media is termed *scalability*. Lev Manovich describes this principle as the ability to create versions of a media object which differ in their size or level of detail [6]. This nature of new media also allows for the creation of versions of a new media object which differ from each other in more substantial ways. In swarm robotics, Murata et al. [26] describe scalability to be a remarkable consequence of the modular structure of the agents in a swarm and the system itself. In this case the size of a swarm is changeable by the number of modules in it as this is vital in order to achieve the best configuration for the task at hand. Moreover, Rubenstein et al. [27] describe scalability as the condition that all of the operations of one robot should work on the collective as a whole without the need for human intervention or individual attention to the agent. If they do, the robot is called *scalable*. In the cited paper, several examples of scalable computations are presented. For instance, the authors present a collective programming of the behaviour in a swarm by using an infrared communication channel, which removes the need for each agent to be programmed separately. The authors also present another example of a scalable operation in regard to the power control of an agent, whereas in order to remove the need for human intervention, a charging dock is introduced for the swarm to recharge itself autonomously. Furthermore, Bjerknes et al. [28] argue about the application of the scalability principle in relation to the size of the swarm. They present arguments as to why the so-far-assumed-to-be-true concept that the swarm decision-making system based on local sensing and communication is only natural to lead to swarms scalable to large numbers of agents, is actually not true in several different cases. One of those shows that a large number of robots in a system would be less beneficial in the case of self-repair and self-configuration since it would increase the swarm's failure rate. They argue that at some point the swarm would 'die under its own weight', thus rendering the scalability principle not true in this particular case.

Just as new media is highly customisable to fit individual needs by creating different versions of one and the same object, the swarm robotic system can either be reconfigured to suit the personal demands (cost, functionality) when targeted to non-professional or everyday usage (e.g. simple cleaning tasks) [29], or it can be modularly reconfigured when it comes to the execution of specific tasks or missions (e.g. exploration of large unknown areas, surveillance, rescue, coordinated weight lifting).

In short, the variability principle is derived from the modular structure and the automation attribute of new media. This principle describes several qualities of the new media object that include its storage in a database, its branching type structure, its scalability and hypermedia. All of those concepts are also applicable in swarm robotics and again emerge from the modular structure and the level of automation in a swarm.

**Transcoding**

Transcoding is the fifth and final Manovich's principles of new media. It is the most evident result of the first principle of numerical representation and it represents the machine-readable information describing the interface of a new media object. It also depicts the new and distinct structure of new media as consisting of two autonomous and mutually influential layers: a *cultural layer* and a *computer layer* [6] (Figure 6). The cultural layer displays the information in a new media object in a way that is comprehensible (images, text, etc.) to the human user while the computer layer turns the same information into a machine-readable language (functions, variables, arrays, binary code, etc.). Since the two layers are strongly dependable on each other, they also become mutually influential. With the constant advance of the hardware and software specifications of a computer system on which the computer layer depends, new opportunities arise for creating different or variant types of the cultural layer of the same object. This interconnectivity defines the creation of a new computer culture where the new media object is a blend of meanings for human and computer. Hypermedia is also a particular case of the variability principle previously described in this paper and is in fact also a distinct example of the transcoding principle since the data and navigation characteristics of its structure exist separately. Another case in point of the transcoding principle is the modular structure of a new media object. The analogy with a computer programme supports this statement as, similar to a new media object, a programme consists of small, autonomous modules which in turn consist of even smaller, autonomous objects. It can be said that the most general definition of transcoding is the translation of something from one format into another [6].

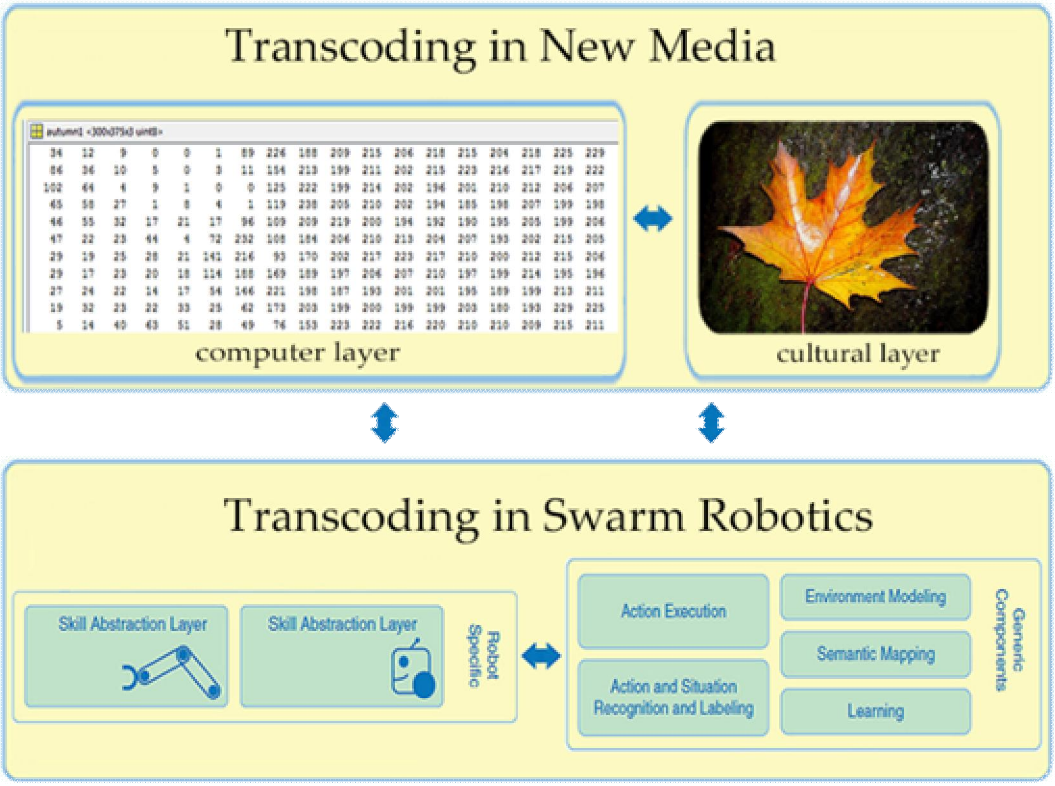



**Figure 6.** Transcoding principle: a visual representation of the analogy between the different layers constituting the fields of new media and those of swarm robotics [13]

However, in order to understand how the transcoding principle works in swarm robotics, it is necessary to explain the structure of the agents building the system. Each swarm agent's hardware is made of different layers. The first layer deals with the information gathered from the sensors and the second layer translates it into a machine-readable language. However, in swarm robotics it is also possible to have a third layer which is responsible for the robot's self-assessment. The work of Kunze et al. [30] illustrates the principle of layered topology. It describes a way to connect high-level action instructions with low-level robot descriptions in the structure of a robot's manipulators. By doing this, the researchers tried to input in the robot's system a certain amount of knowledge about itself that would enable it to assess whether it would be able to perform the required action.

Apart from being a necessity for an object to be defined as a new media object, the layered structure of a swarm agent is also an addition to the branched topology of the code defining the behaviour of the agent. As previously discussed, the code defining the behaviour of a robot is structured around context-driven choices. For instance, when the swarm agent encounters an obstacle, the information about its surrounding is gathered by the sensors and translated into numerical data, which further enables the robot to search into its predefined database of actions in order to decide what to do next regarding the environmental context. However, in order to use the predefined database of actions, the robot should possess certain knowledge about its existence. One of the ways to achieve this is with the so-called *Semantic Web*, which organises the available data, hence enabling an agent to create knowledge about itself without the need of a large-scale artificial intelligence [31].

Similarly, the work of Waibel et al. [13] describes the RoboEarth database as having a three-layered architecture. The first core layer is a server storing the RoboEarth database comprising global world model, reusable information of objects, and environments and actions linked to semantic information. In addition, the semantic information also provides Web services enabling the robot to conduct basic reasoning. The second layer of the database is comprised of generic components which are a part of the robot's local control software whose main function is to allow the agent to interpret the action recipes embedded in the distributed database. This layer also extends and enhances several of the robot's capabilities including sensing, modelling, reasoning and learning. The third layer implements skills and uses a skill abstraction layer to provide an interface to the robot's specific hardware-dependent functions (Figure 6). In addition to that, the information in RoboEarth is linked on several levels. For example, the semantic description of an object, its properties, its relation to other objects and instructions for manipulation can be linked to the three dimensional model of the object. This provides not only the wiring between the different levels of the robot's architecture involved in the recognition of an object and the execution of the task at hand, but also the connection between the robot's layered architecture and the layered structure of the distributed database.

The work of Juarez [31] illustrates the use of *Semantic Mediawiki* to associate wiki pages with the agent itself and each of its components. Also, the paper argues about the efficiency of such a system and the demands it poses on its users. Furthermore, the author proposes an improved model called *RoboDB*, a system for creating knowledge about robots and their capabilities. This can be achieved mainly by using *ontologies*, which are at the core of knowledge generation in the Semantic Web. Ontologies are used to formally describe a group of objects linked together and the vocabularies used to embed knowledge in this domain. They are also means of representing semantics of documents as well as structuring and defining the metadata terms collected by RoboDB. Ontologies are closely related to the concept of transcoding in new media since they describe different layers of the robotic entity, the relationship between those layers and the properties or attributes that the layered topology may have. Moreover, the use of ontologies enables the performance of semi-automated reasoning. This is important as it increases the level of automation possessed by an agent and hence its ability to perform tasks in a more intelligent and accurate way at a human concept level. On a more profound layer, the protocol behind reasoning with ontologies is called *Description Logic*, which represents a variety of formal knowledge representation languages which describe the concept and techniques of computing the relationships between the different layers in an agent.

Furthermore, Juarez [31] also describes a concept in robotics called *motor schemas* as every action or behaviour the robot exhibits. The motor schemas comply with several different levels of abstraction such as *sensory schemas*, which deal with the low-level input from the robot's sensors and the actuator output, and *perceptory schemas*, which work at high-level abstraction in order to process the information gathered from the sensory schemas. The work of Tang and Parker [32] takes this concept one step further by introducing a variation of its application to swarm robotics in the context of task planning and execution. They extend the capabilities of the old system and create various level schematics dealing with different sensors and communicators within the swarm. Moreover, they also propose a way of labelling the capabilities of the agents within the swarm and then use this to match them within the system in order to construct a task execution plan.

One more example of the layered structure of a robot is described by Sablatnog et al. [33]. The introduced middleware platform Miro there uses three levels of abstraction in order to describe a robot's capabilities: device layer, service layer and class framework layer. The device layer extracts information gathered by the robot's sensors and actuators, the surface layer deals with the robot's interface and the class framework layer deals with the processing algorithms.

However, the previously discussed layered topology can also be applied to a swarm of robots as a whole as shown by Alunni et al [14]. The author describes a certain type of topology where a swarm consists of three levels of communication, two of which are administrative and one is responsible for object detection. The top level of the swarm is called level zero and is addressed as 'the queen'. Its function is to govern and direct the entire swarm and more specifically the second level, which is called 'the worker' (or level one) and is directly under the queen's control. It has the basic functionalities of level zero but is only in charge of a sub-section of the map. The third level (or level two) is called 'the scout' and represents the physical interface of the swarm and the surrounding environment. It is also the only level equipped with sensors for scanning the external world. Each agent is only able to communicate to its 'parent' or 'child' level. The major advantage of using this typology is the increase in scalability of the system. This topology model also simplifies communication in the swarm in case new agents should be added as they would be presented as new layers and would not affect the connections throughout the swarm as a whole.

This shows that the concept of layered architecture of an agent and using contextual information, ontologies and semantics in order to translate the data gathered by different layers in a way that would be understandable throughout the entire system are common practice in robotics and are also applicable to swarm robotics.

## EXPECTATIONS

A direct consequence of the new media structure of a swarm robotic system is that it broadens the application areas of robotics. For example, a swarm of robots not only have the structure of a new media object, but it may also be used to create new media interactive installations. The UMwelt-VIRUtopia [34] uses swarm robotics in an interactive installation which is specifically designed to create a dialogue involving space, sound, light and the audience. Its purpose is to bring up questions concerning the way people perceive the combination of robots and sensing stimuli – whether or not the swarm architecture and patterns can be changed through interaction, and overall, if those approaches can be used to reprogramme space and behaviour or even a new experience and a new world. Another possibility would be to use swarm robotic systems as new tools for expression for new media artists and designers, or new ways to build upon work that has already been created in the field. For instance, an interactive installation and a research project in human robot interaction called *Swarming Heads* is based and built upon Stelarc's project 'Prosthetic head' [35]. In the Swarming Heads installation the robots were capable of detecting humans and certain gestures to which the robots were programmed to respond. However, each robot was designed as an individual and so it happens that, at times, it could behave quite unexpectedly due to the external stimuli it received [36]. Another example of an interactive installation is that of Michael Theodore and Nikolaus Correll called *Swarm Wall* [37]. It was designed to respond to human presence in an interactive way. Moreover, when it 'thinks' it is being ignored, it would try harder to catch the audience's attention. The people behind this installation have also created an active lab where students from various disciplines in engineering and arts collaborate in order to create cutting-edge applications of robotics and artificial intelligence. Their motivation behind this project is that even though the difference between art and science is very significant, the goal of both fields is to discover new things. Furthermore, artistic exploration can help engineers ask questions they would not have otherwise asked [37]. An example of this is Albin's research on musical swarm robot simulation strategies [38]. One of the goals of his work is to determine the legibility of the motion to musical mapping. However, the solutions to the simultaneous localisation and mapping problems encountered in this study may also be used in other scenarios such as search and rescue or exploration tasks [39]. It is highly possible that the problems faced in the study of the robots' motion to music would be different than the ones faced in other more scientifically oriented scenarios. However, implementing those solutions in different missions may significantly enhance the robots' overall performance. This is an example of how the new media structure of a swarm robotic system can widen its range of application possibilities, which is a cause of the emergence of new types of problems whose solutions improve the overall performance of the robotic teams.

Besides their use in music, the work of Bornhofen et al. [40] discusses the use of swarm robotics in the creation of art. An example is Disney's project called *Display Swarm* [41]. It introduces the concept of an innovative display design comprised of a mobile robot swarm of agents called *Pixelbots*. Each agent of the swarm acts as an individual pixel with controllable colour in a dynamic image or animation made entirely by robots (Figure 7a). In addition, the authors have also developed an app for iPad allowing the users to create a drawing and the robots will shift accordingly so as to recreate it. During the development of this project the authors also significantly contributed to the research on collision avoidance [42] and pattern formation in swarm robotics [41]. Another similar example is the work of Kronemann and Hafner [29] discussing *Lumibots* – a swarm of small autonomous robots with high sensitivity and reaction to light. Their purpose is to create images that are ever changing due to the UV-LED at their tail (Figure 7b). Yet again, those are very simple robots programmed to follow the trail of each other. Nevertheless, observing such processes can raise questions that may help enhancing the robots' performance in more diverse applications in formation control, coverage and flocking [43].

In sum, the use of swarm robotics in the field of new media presents the swarm robotic system as a novice tool for the new media artists and designers to express themselves, convey a certain message or build upon famous works of previous authors in the field. However, the new media structure of a swarm robotic system not only expands the application possibilities for a swarm robotic system, but also presents a different environment with different situations, thus significantly enhancing the performance of the system in various types of applications.

a)

b)

**Figure 7.** The use of swarms in interactive installations: a) Disney's *Display Swarm* [41]; b) Lumibots [29]

## CONCLUSIONS

Not only can swarm robotic systems be perceived as new media objects, but also the collaboration between the fields of new media and swarm robotics can be mutually beneficial. A novel approach to perceiving the field of swarm robotics by comparing it to the current vastly expanding field of new media has been presented. The authors of this paper support the notion that through collaboration between swarm robotics engineers and new media artists, novice, cutting-edge applications for both fields can be achieved. While the fields of new media and swarm robotics are generally considered to be relatively different, the aim of this paper is to bridge them and prove their resemblance. With the fulfilment of such concept, the authors believe that the connection between new media and swarm robotics can prove useful and enhance future projects and research into both fields.

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