A Bio-inspired and Altruistic-Based Framework to Support Collaborative Healing in a Smart Manufacturing Shop-Floor

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Abstract. Biologicalisation defines the analysis of biological patterns as a source of inspiration to model intelligent manufacturing systems. Due to their inherent adaptability, these design representations are highly desirable considering the increasing complexity of modeling current manufacturing solutions. Contributing to the idea of self-organizing and autonomous shop floors, we present a framework that aims to support the collaborative healing of manufacturing resources. This has been inspired on the altruistic behavior of bats in which social care is demonstrated (e.g., in bat colonies) even at the cost of individuals' fitness/health. These ideas are conceptually showcased in an emergent automation manufacturing application, i.e., peer-to-peer energy sharing in automated guided vehicles. Some conclusions, and potential future research are discussed at the end of the paper.

Keywords: Biologicalisation · Self-organization · Smart Manufacturing · Self-healing · Artificial Intelligence · Altruism · Collective Behaviour

1 Introduction

Biologicalisation considers the use of "bio-inspired principles in intelligent manufacturing applications to fulfill their full potential" [1]. The collective intelligence of biological systems can be used as a source of inspiration to design self-organizing, self-adapting, or self-healing mechanisms [2]. Those are key issues in the fourth industrial revolution because of the increasing complexity in their engineering design [3]. Some cases of application include the immune system, where immune cells are used as analogies to define intelligent agents that perform distributed monitoring and diagnosis [4]. Stigmergy, where ant pheromones [5] are used as a mechanism to indirectly coordinate control tasks, or the chemical reaction model where the self-assembly of manufacturing modules is provided similarly to how molecules in a solution react [6].

In healing operations, this collective biological behavior can be used as a source of inspiration to define collaborative self-repair of robots, for providing cures, for sharing

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spare parts, or even in peer-to-peer energy-sharing problems. This has been generally elusive considering the context of biologicalisation in smart manufacturing applications.

Thus, the definition and analysis of these ideas in the form of a conceptual framework are the general motivation of this work, where the social altruistic behavior of vampire bats is used as a metaphor to define two basic roles in intelligent manufacturing resources: Altruistic/Donor and Recipients. Those are the base to describe a collaborative healing environment where the ultimate goal of a highly adaptable and flexible manufacturing system can be achieved at the cost of a minor decrease in individual resource fitness. The description of these roles is essential, especially in emergent manufacturing infrastructures e.g., shop floors with flexible transportation of tools and consumables [2, 7]. See Fig. 1 where a basic overview of this idea is shown and applied to a peer-to-peer energy-sharing problem under the context of the matrix production concept [8]. These ideas are also showcased in a simulated scenario using the software NetLogo. Various conclusions and potential future research directions are derived from these results. The next sections of this paper are driven by the following research question (RQ) and hypothesis (H).

- **RQ:** How can a manufacturing framework for healing operations be implemented while denoting autonomous and collaborative collective behavior?
- **H:** A framework with the preceding characteristics can be implemented if certain properties of the reciprocal altruism of vampire bats are studied and represented as a collective healing problem in a shop-floor.

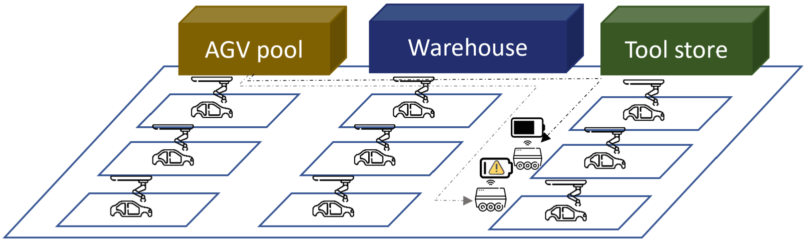

Fig. 1. Peer-to-peer energy sharing in the matrix production concept

2 Relation to Connected Cyber-Physical Spaces

Cyber-physical spaces are defined as" engineered systems operating within physical space with design requirements that depend on space" [9]. Due to their inherent design complexity to generate autonomous and adaptable solutions, i.e., in the context of manufacturing systems, it is necessary to consider new ways of engineering inspiration. Solutions based on collective intelligence, where group intelligence emerges from individual collaboration (e.g., in biological systems) are a promising line of research in this direction. This can generate new ways of adaptability, flexibility, robustness, and resilience for systems that aim to be highly interconnected (i.e., cyber-physical).

3 Altruism in Vampire Bats: A Biologicalisation Concept

This section introduces the origin of the idea of altruism and reciprocal altruism and represents the road-map, and some required technologies in order to model autonomous collaborative healing solutions. Fig. 2 shows the overall concepts and ideas of this section.

– *Altruism and reciprocal altruism:* In one of the genuinely classic articles in the subject of altruism research, Trivers (1971) [10] made the discovery of the reciprocal altruism hypothesis. He coined the term "altruism" to describe actions that benefit someone other than the person acting in an altruistic manner. He uses evolutionary biology to present concepts of costs and gains. He argued that charitable acts frequently result in favors being returned, which can result in a gain for the initial giver. This suggests that doing good actions in strategic networks can result in favors being returned, which would then improve performance both on an individual level and community/social level [11, 12].
– *Reciprocal altruism in Vampire bats:* In situations where there is a risk of death, such as starvation, and it is impossible to predict which individual will be successful on any given occasion, Trivers (1971) [10] argued that reciprocal altruism will become an evolutionarily stable strategy but only if those who are successful in obtaining food get more than they immediately need, and share it with a neighbor.

  One of the noble examples of altruism connection has been observed in vampire bats. These types of bats subsist by sucking the blood off cattle hides, but they frequently go without food. They can survive without food for up to three nights before they perish [13, 14]. Ordinary vampire bats only consume blood and die after 70 hours of fasting, although hungry bats frequently receive food from the regurgitation of their roost-mates. Sharing food among vampire bats is a behavior that happens naturally, is energy-intensive, occurs between kin and non-kin, and may be artificially induced [15]. This behavior has the potential to be a great model for studying the enforcement of cooperation and connection in the societal and industrial domain, as it represents a high level of collaboration, autonomy for individuals, and successful survival especially in the crisis of sufficient supplies.
– *Altruism and reciprocal altruism within the autonomous manufacturing domain:* An autonomous or self-organized manufacturing shop-floor refers to a system that can fulfill its inherent processes (handling, maintenance, control) without human assistance (external intervention). The manufacturing needs are met by autonomous production systems that have the ability to self-manage. Also, an intelligent architecture enables the reuse and sharing of independent task-specific modules which can decrease the manual engineering labor required for configuration and reconfiguration [16, 2].

  Effective communication and collaboration among autonomous vehicles is one of the key criteria in order to fulfill sustainable, self-organized, and collaborative manufacturing, specifically in the time of need for help such as energy ran out, tool repairs, or load sharing. Here is the area in which Altruism has innovative ideas to offer. The intra-group cooperative behavior of reciprocal altruism guarantees that the non-relative agents get assistance in pairs in their time of need [17]. In this way it assures self-management and continuous collaboration within the manufacturing resources, this happens in situations where agents have a solid and stable connection and bond to make autonomous decision-making.

– *Technologies to support altruism and reciprocal altruism:* To make manufacturing processes autonomous, re-configurable, and flexible new technological enablers, and computational tools are constantly being developed. Cooperative altruistic behavior can be assisted by many of these technologies. Intelligent cooperative agents can abstract specific resource awareness and allow distributed communication. Intelligent manufacturing modules can be re-used and shared, providing the capacity of reallocating in case of need. Smart perception systems and artificial intelligence methods allow the monitoring of physical variables to have awareness of the status of individual resources. Hardware like wireless energy chargers may allow the sharing of energy consumption between different resources. Thus, the implementation of altruistic behavior is possible within the current landscape of technologies. However, applying the altruistic model in the context of a smart manufacturing shop-floor requires a concrete framework. This will be discussed in detail in the next section.

4 Framework to Support Altruistic Collaborative Healing

The proposed framework relies on the definition of intelligent agents capable of social ability (communication) and autonomous decision-making. It has been inspired by previous ideas of altruistic behavior for multi-agent systems [18–20] and the context provided of altruism in vampire bats. The main differentiator of the proposed framework is its examination under a self-healing smart manufacturing context. Main roles and components are defined below. In this work an agent can be considered as an entity in the shop-floor capable of performing any manufacturing operation, e.g. transport, assembly or machining. Fig. 3 presents an overview of the conceptual framework for collaborative healing.

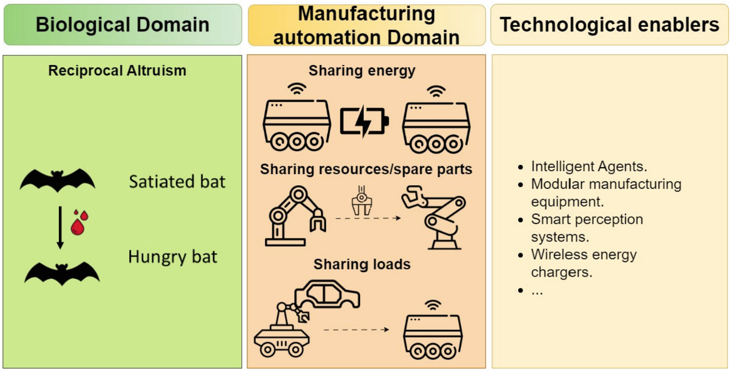

Fig. 2. Bioligalisation of a healing process based on the concept of altruism

4.1 Definition of Agents' Roles

The framework is built under the definition of two main roles.

– *Recipient agent:* Entity that has or is going to have a malfunction or anomaly and requires assistance to continue with its current task.

– *Altruistic/Donor agent:* Entity that in ongoing conditions is capable of assisting a recipient agent, either by providing a cure or by sacrificing part of its fitness while successfully fulfilling its own task.

4.2 Definition of Main Components

The agents of the framework are built within six main functional components:

– *Current task:* Ongoing activity or set of activities assigned to an agent e.g. transportation, assembly, etc. An idle state denotes a momentary stop of the specific task to help or to receive help. See Fig. 4a where a general model of a task is described.
– *Health monitoring:* The element in charge of continuously tracking the health status or a type of potential failure an agent can have. If any problem or failure is identified, an altruistic signal will be emitted looking for a candidate altruistic agent that can provide support. Examples of monitoring units are the remaining energy of an AGV, the remaining useful life of a tool, the inability to carry a load, etc.
– *Remaining altruistic time (lead time):* Time in which an agent can show altruistic behavior. Difference between the estimated time in fulfilling a task and its due date. It can be referred to as the lead time or the maximum allowed cycle time.

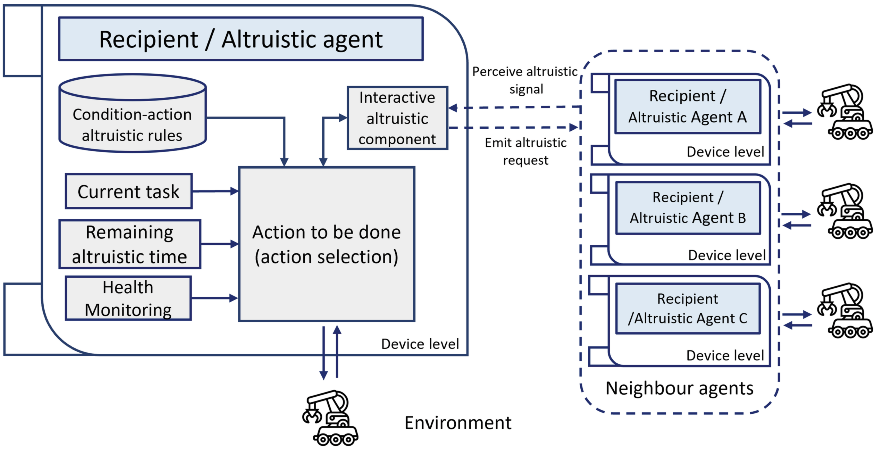

Fig. 3. Framework for collaborative healing based on altruistic behavior

– *Condition-action altruistic rules: a* Set of rules (behaviors) that can be performed by an altruistic agent in order to provide healing support. These are launched once an altruistic signal has been detected and the altruistic task's feasibility has been checked. As there are many different strategies that can be applied in a healing context, this can be treated as a multidimensional decision tree, where each dimension can represent a topic for altruistic support, e.g., energy sharing, load sharing, spare parts tool exchange, etc. These rules should also contemplate restrictions in the applications of certain behaviors. See Fig. 4b where a generic model of decision tree is described.
– *Interactive altruism detection:* Component in charge of both perceiving altruistic signals and emitting altruistic requests.

– *Action to be done:* Main decision-making entity. It takes as input the monitoring component, remaining altruistic time, and interactive altruistic detection to decide if the agent's behavior should be Recipient or Altruistic. Also, it can choose a proper altruistic rule based on the environmental context. It is also the execution unit and interface with the physical resources.

4.3 Execution: Activity Diagram

During the execution of the framework, various stages must be considered.

First, when an anomaly or failure is detected by the health monitoring component, a healing request is launched to the action selection component. This will analyze the feasibility of stopping its primary task. When stopped, a signal will be emitted asking for an altruistic agent and with the necessary requirements for its healing.

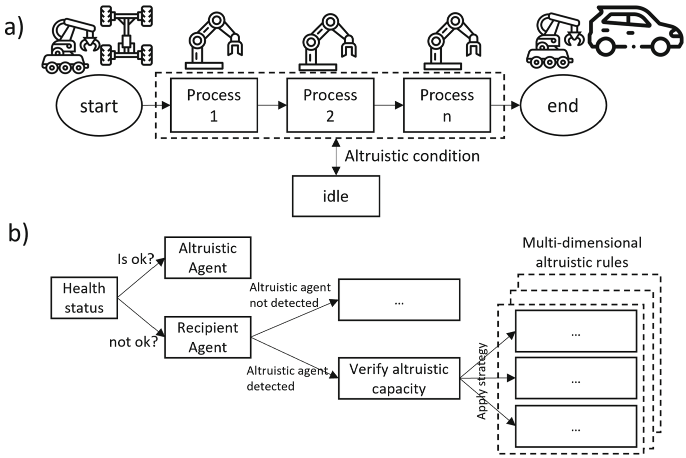

Fig. 4. (a) Task modeling as a sequential process and (b) Decision tree modeling for the condition-action rules

Agents that can perceive this request will decide whether to assist the recipient agent based on their own capabilities i.e., remaining altruistic time, own health monitoring, and current task. If the altruistic request is accepted, the now-called altruistic agent will stop temporarily its current task (idle state). After that and considering the altruistic request, a proper altruistic behavior(s) will be applied from the predefined condition-action rules, and if needed it will approach the recipient agent. Once close enough, the required altruistic behavior will be applied. After that, both the recipient and altruistic agents will continue their normal tasks. Figure 5 summarizes this logic as an activity diagram.

5 Experimental Use Case: Distributed Peer-to-Peer Energy Sharing for Autonomous Mobile Robots

In a shop-floor with flexible transportation mobile robots may have different tasks and therefore different residual energy. Energy can be also restricted by the number and location of charging stations. In extreme conditions (e.g., a rush order) running out of energy can mean a delay or a bottleneck in production. Motivated by this and by previous works in this field [21–24] we decide to showcase the proposed collaborative self-healing framework in this context. Important requirements and assumptions are made to simplify the demonstration of this concept:

– Mobile robots can communicate with each other.
– The collaboration is driven when a specific energy threshold is reached.
– The collaboration is type reactive at this moment.
– There is a priority on sharing energy rather than coming back to a charging station.
– There is instantaneous energy transference with 100% efficiency.

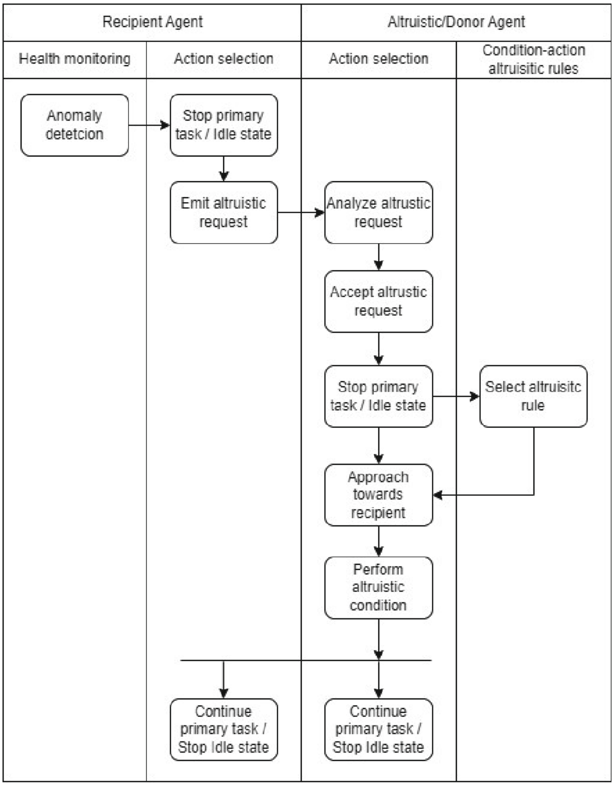

Fig. 5. Execution activity of the proposed framework

The use case consists of two mobile robots. Each of them has a particular task and both tasks must be executed at the same time (transport material to a cell and come back to the home position). One mobile robot has full energy, while the other lacks the energy to complete the task. In this context, the idea is to understand the results of the proposed framework in terms of cycle time and total energy used under 3 scenarios: (1) without altruism, (2) with altruism, (3) with altruism, and with a restriction. In the latter case, the restriction launches the altruistic behavior just when there is a predefined distance between the altruistic and recipient entities.

5.1 Simulation, Results, and Discussion

Previous scenarios were implemented using the software NetLogo, commonly used to study complex behaviors in multi-agent systems. A simple interface was designed to visualize the interaction of the agents, energy consumption, and cycle time in units (u). Figure 6 presents a sketch of the simulation implemented.

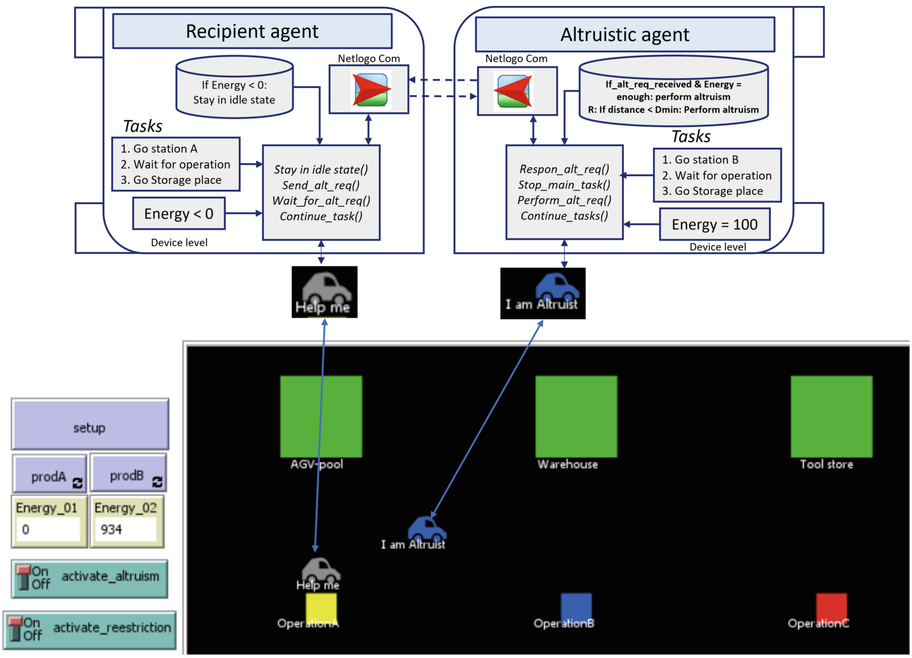

Fig. 6. Simulation made in Netlogo

Preliminary numerical results of the simulation (see Fig. 7a and Fig. 7b) show that altruistic energy sharing can indeed be used as a strategy to complete a task in a case of emergency. In this example, when altruism is not applied the mobile robot 1 cannot autonomously finish its task (which will imply the need for extra manual work). When the altruistic property is applied Robot 1 will be helped by Robot 2 (it will share energy). It is important to note also that, even if altruism is applied, some restrictions are needed to improve the performance of the process (e.g., which is the optimal condition to help another entity while maintaining a certain level of optimal conditions in the process).

In this example, the distance restriction reduced the overall consumption by 49 units (18%) (altruist is activated just when the mobile robot 2 is close enough to the mobile robot 2) compared to the approach that did not use the restriction. A similar result was obtained with the cycle time (time needed for product manufacturing) i.e., 3,37 units of time were reduced in the manufacturing of product 2 (at the cost of a slight increment in the product 1 cycle time). Overall, we can state that these show the potential of this concept. Altruistic collaborative healing can be very effective in emergency situations and can promote higher levels of adaptability and flexibility. More experiments need to be done to understand in detail its potential, possible limitations, and specific scenarios of application.

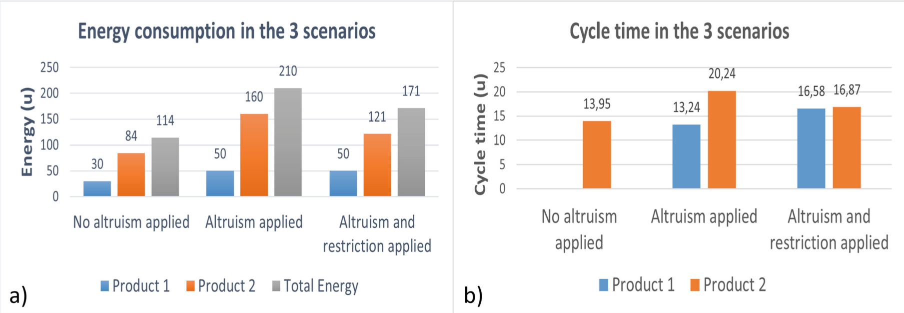

Fig. 7. Simulation results. a) Energy consumption and b) Cycle time

6 Conclusions

The main takeaways of this paper are:

- Introduces a biologicalisation process for collaborative self-healing inspired by the altruistic behavior of bats.
- Presents a framework that conceptualized this idea providing two main roles to the manufacturing resources: Recipient and Altruist.
- Preliminary results of this concept are showcased using the software NetLogo in a distributed peer-to-peer energy sharing problems with autonomous mobile robots.

Future ideas in the direction of the paper include creating an optimization component that can provide the best altruistic rule based on the context of the problem.

Providing a cost-benefit analysis to understand the economic benefits that this idea can provide to a real manufacturing plant. A deeper specification of some components of the framework e.g., "monitoring component" that can be based on a machine learning approach to predict a failure in one of the agents. The contextualization of the approach under a human-centric design [25] is highly relevant considering initiatives like Industry

5.0. This idea needs to be showcased in other applications e.g., load sharing and tool sharing to provide a more generic representation of mutual collaboration (altruism) and also to understand its real potential and possible limitations. Finally, this work can be placed under the context of established control strategies e.g., Holonic manufacturing systems or Evolvable Production Systems. This can make the framework more meaningful in regards the machine control which can be very complex and context dependent.

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