Bio-Inspired Protocols for Embodied Multi-Agent Systems

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Abstract: Bio-Inspired approaches and techniques are being used in different domains and applications in artificial intelligence, including the agent domain. Some agents are able to move from one system to another to establish new relationships. In biology, ecological relations are concepts responsible for classifying the relationships between living beings in an ecosystem, depending on the behavior and function that each one can assume. The objective of this work is to propose bio-inspired protocols based on ecological relations: Predation, Inquilinism, and Mutualism. These protocols aims to preserve agents' knowledge as they can live as a tenant in another physical body waiting for a similar hardware to predate, or acquire and transmit knowledge by interacting with other agents while sharing the same physical body. To validate these protocols, a study case and a scenario are implemented, tested, and evaluated in a real environment.

1 INTRODUCTION

The biology has inspired in so many ways Computer Science and Artificial Intelligence fields contributing to the development of new concepts, algorithms, and techniques capable of improving learning capabilities and social organization applied in different domains of applications. Intelligent systems can become increasingly efficient by applying bio-inspired approaches in their performance and group work for achieving goals (Zedadra et al., 2016).

The agent approach also has some similarities with biology concepts, such as reasoning, cognition, and interactions between agents. The agents are independent and proactive entities with cognitive ability to make decisions based on what they can perceive in the environment and communicate with other agents. Multi-Agent Systems (MAS) are composed of multiples agents interacting with each other, and they are capable of solving situations collectively (Wooldridge, 2000).

Some MAS can be closed or opened depending on the characteristics that agents can assume. An open MAS allows agents to enter, interact, and leave it in anytime. It provides that agents from a MAS can share knowledge (beliefs, intentions, plans, and goals), and help each other to achieve a common goal (Huynh et al., 2006) in another MAS. It can reduce the number of messages exchanged using an external infrastructure in case of MAS in distant locations, since an agent moves itself to a specific MAS instead of sending messages using a network connection, for example. Therefore, an open MAS intrinsic leads to agents capable of moving from one MAS to another.

In biology, ecological relations define and explain how interactions between living beings occur in an environment. These relationships happen among living beings of the same species or not, and it allows members of a particular community of living beings to relate to other ones from different communities, expanding the relationships to an ecosystem level (Begon et al., 2006). Similarly, an open MAS allows the entrance and the exit of agents in its system, enabling a dynamic integration of new agents with the existing ones (Huynh et al., 2006).

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We assume the existence of an Embodied MAS, which is a physical device composed of resources, controlled by an embedded open MAS. It can be compared to an Embodied agent (Rickel and Johnson, 2000), which is a single agent incorporated in a physical device. However, the agent is not part of an embedded MAS. Then, one can define an ecosystem for Embodied MAS as a group of Embodied MAS situated in a physical environment, and capable of communicating and interacting with each other.

There are related works inspired by biology concepts in the agent domain to provide techniques and algorithms to increase the level of interaction and communication between MAS that act upon the same environment (Günay et al., 2015), allowing agents of different systems to communicate and interact. A foraging situation (search of food resources based on survival instincts) (Zedadra et al., 2016) is presented where different open MAS act upon a simulated environment. It allows agents from different MAS to interact and perform complex tasks. These works do not consider the risks of dealing with a real environment. Since the real environment is unpredictable, they do not offer mechanisms to preserve the integrity of the agents' knowledge in case of some incident.

This work proposes three protocols inspired by ecological relations for transferring agents between distinct Embodied MAS. The embedded open MAS of the Embodied MAS has agents that can enter or leave in a synchronized way depending on the protocol activated. The protocols allows Embodied MAS to preserve their acquired knowledge during a situation where a menace exists or even if its physical parts are damaged. Besides, it is possible to exchange their knowledge by moving part of their systems to a host for learning or sharing abilities. The main contribution is an architecture to create and assemble physical devices using embedded MAS capable of transferring agents using protocols inspired by ecological relations.

The remainder of this paper is organized as follows. In section 2 the related works are discussed, in section 3 is presented the the bio-inspired protocols with each ecological relations implemented. Next, in section 4 shows the formalization for the bio-inspired protocols, in section 5 is presented the prototype used in the experimental evaluation and the results of the performed tests, and Section 6 shows the conclusion.

2 RELATED WORKS

Some works already use the bio-inspired techniques and Multi-Agent Systems applied in real environment (Ferri et al., 2006; Chen et al., 2009). New technologies and methodologies have emerged (Zeghida et al., 2018; Günay et al., 2015) inspired by biology and aiming to improve the usage of Open MAS.

A framework (Günay et al., 2015) allows agents to create a compromise protocol dynamically at runtime, which allows the agents to change a compromise assumed in the MAS's design time or assume a new one. Considering open MAS, this dynamic protocol allows agents transferred to another MAS to create new compromises and update those in the original MAS at runtime to these agents to better adapt to the current MAS. Considering bio-inspired MAS, there is a generic multi-paradigm model for bio-inspired systems (Zeghida et al., 2018) to compare an agent with a living being giving them some abilities that the living being has. These abilities, such as evolution, self-correction, and decentralized control, improve the agents' capability to acquire new knowledge and autonomy. Although, if the MAS is damaged, these agents can not preserve their knowledge.

A bio-inspired foraging algorithm is presented involving agents that can cooperate and perform complex tasks by breaking them down into small and simple sub-tasks (Zedadra et al., 2016). It characterizes the act of capturing and searching for food in a particular storage location. Despite being a bio-inspired application and allowing communication between agents from different MAS, this work does not have a mechanism for preserving agents' knowledge, so if the MAS is damaged, all knowledge will be lost.

In order to employ MAS in a real environment, it is necessary to have architectures that allow agents to communicate with physical devices and a network for providing a communication channel with others MAS. *ARGO* is a customized architecture that integrates microcontrollers and agents to automatically perform actions and capture percepts in a real environment. *ARGO* agents share the same architecture of a Jason agent (Bordini et al., 2007), but they can interface hardware components. This type of agent cannot communicate with agents from other MAS, since Jason framework only provide Closed MAS. For this, *Communicator* agents uses an IoT architecture and middleware that allow establishing communication from this specific type of agent with another one of the same type hosted in another MAS. Considering these agents' characteristics, they can be exploited to build an approach where an Open MAS could communicate with other Open MAS, including transferring agents based on some ecological relations implemented by the bio-inspired protocols proposed. These protocols deal with issues that eventually arise in a physical environment to preserve and share knowledge.

The open MAS approaches are gaining more importance in the agents' literature, allowing different agents from different MAS to communicate, exchange knowledge, and transfer themselves to another MAS (Golpayegani et al., 2019; Amaral and Hübner, 2019). Therefore, the open MAS literature is concerned with organizational structure after an agent transference and the interaction between a transferred agent and the destination MAS agent. Some questions such as how will agents be transferred? Why transfer agents? are not being answered, and these issues are being explored in this work using bio-inspired protocols for transferring agents aiming at preserving agents' knowledge.

3 BIO-INSPIRED PROTOCOLS

This section discusses the bio-inspired protocol proposed based on ecological relations (inquilinism, predation, and mutualism) to be used along with Embodied MAS. Besides, in section 3.1, we show the details of engineering the protocols and how their execution behaves.

In biology, ecological relations (Howe et al., 1988) are the domain dedicated to explain how living beings relate to each other within an environment. For example, some species can live in collaboration with other species in the same environment where both of them get a win-win situation with this interaction, or they can compete for resources or life existence. These interactions occur in a determined place where several communities of living beings constitute a balanced and self-sufficient system named ecosystem (Begon et al., 2006). There are several ecological relations, nevertheless, discussing all of them is out of the scope of this work. However, three relations have characteristics that we point to be useful for agents: Predation, Inquilinism, and Mutualism.

Since MAS are composed of several agents interacting for achieving commons objects or even competing for the same resources in an environment, and each of them may have roles in the system, then we could consider that MAS can be interpreted as a community of agents (Rickel and Johnson, 2000). Furthermore, once it is possible to consider a MAS as a community of agents, we can extend this concept, in this work, to be applied to Embodied MAS, which contains a community of agents responsible for control physical resources and interacts with other Embodied MAS in a real-world environment (Pantoja and Viterbo, 2017). Once different Embodied MAS can interact with each other, one must consider that they are part of an ecosystem of Embodied agents.

We can define an Embodied MAS as a physical device operated by an embedded open MAS composed of multiples agents playing different roles. *Physical* agents are responsible for interfacing physical resources for gathering sensing information and acting in the real world. Besides, they have the capability of sharing the collected information to other agents in the open MAS. The *Communicator* is a unique agent responsible for all the external interactions (including mobility). It is also responsible for activating the bio-inspired protocols. Finally, there are *Traditional* agents without any dedicated ability other than internal communication and interaction between all types of agents. Based on this definition, we assert that these Embodied MAS can make use or be affected by some of the ecological relations mentioned before. In Table 1, it is shown a comparison between the ecological relations from biology and our proposed bio-inspired protocols.

The ecological relations are represented as a set of transfer protocols activated by an Embodied MAS to provide a mechanism for *Communicator* agents to interact with *Communicator* agents from others Embodied MAS for transferring agents and preserving knowledge. How they interact will establish the ecological relation adopted. For example, in situations where an Embodied MAS has its physical resources damaged but it contains valuable information (its mental state), it can activate a protocol for transferring itself to an existing Embodied MAS with the same physical resources, taking full control of it. If the resources are not the same, it can co-exist with the target Embodied MAS by interacting and learning from its agents, or it can wait for a new Embodied MAS appear in the ecosystem with the same kind of resources to get control over it.

An Embodied MAS (Sender) activates a protocol for transferring its agents to another Embodied MAS (Receiver) in these situations. The Sender saves all agents' mental states that will be transferred and using the *Communicator* agent transfers them to the Receiver. This step is common for all protocols.

The final step depends on which protocol has been activated. In the predation protocol, all the agents will be copied from the Sender Embodied MAS — with their actual mental state — and sent to another Embodied MAS. All agents of the Sender and Receiver Embodied MAS will be killed, and the agents received from the Sender Embodied MAS will be initialized in the Receiver Embodied MAS. In the inquilinism protocol, all agents from the Sender Embodied MAS is sent to the Receiver Embodied MAS, where they co-exist with the existing ones. In this

Table 1: Comparison of the ecological relations definition by biology and the ecological relations in the bio-inspired protocols.

Ecological relations	**For biology (Begon et al., 2006)**	**For bio-inspired protocols**
Predation	Predation is an inharmonious relationship, where a living being (the predator) uses of its instincts to hunt and prey on another living being (the prey).	In the predation relation, all agents are transferred to another Embodied MAS with the intention of predating and dominating the second one eliminating its existing agents to get control of its physical resources.
Inquilinism	Inquilinism is a harmonious relationship, where a living being (host) serves as shelter for another one (tenant) without being harmed. The tenant uses the host's body for protection permanently or temporarily.	In the inquilinism relation, an Embodied MAS sends all its agents to another one for protection and shelter until a similar Embodied MAS be identified. Besides, the transferred agents cannot interfere in the other agents' activities.
Mutualism	Mutualism is a harmonious relationship, where both living beings involved in the relationship benefit from it. This mutual benefit becomes indispensable for the survival of the involved in the relationship.	In the mutualism relation, an Embodied MAS can send an agent, a group of agents, or the entire MAS to another Embodied MAS to learn or transmit knowledge. The transferred agents should co-exist during a specific time, and then they return to their original Embodied MAS.

case, all agents from the Sender Embodied MAS are killed. Finally, the mutualism protocol, an agent or a group of agents will be sent to the Receiver Embodied MAS to exchange knowledge *in loco*. After that, these agents should get back to the Sender Embodied MAS and no agents are killed. The process of activating the protocols is described in Figure 1.

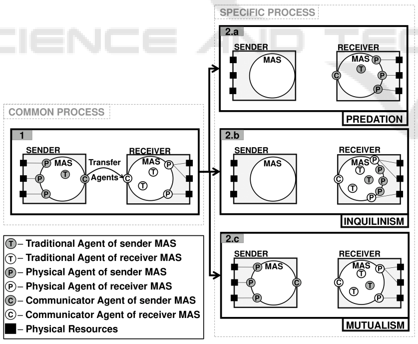

Figure 1: Transport of agents using the bio-inspired protocol.

3.1 Implementing the Bio-Inspired Protocols

This section describes the proposed bio-inspired protocol's implementation, explaining each ecological relation in the protocol (predation, inquilinism, and mutualism), and how they are activated. For activating and executing a protocol, it is necessary to employ a reliable communication infrastructure where agents from one Embodied MAS can exchange information or move to another Embodied MAS. The ContextNet middleware provides a server-side communication layer using the Scalable Data Distribution Layer (SDDL) middleware (Endler et al., 2011), which extends the OMG's standard Data Distribution Service (DDS) addressing real-time applications and embedded systems. It allows multiples devices connecting to a network at the same time, dealing with all network issues such as reconnection and scalability.

Considering this, ContextNet allows multiple Embodied MAS to connect in the same communication infrastructure for interacting and exchanging information. Besides, an Embodied MAS uses ContextNet to communicate with other Embodied MAS, it can have some agents capable of moving to another Embodied MAS, and it also performs a bio-inspired protocol.

This work uses the Jason framework (Bordini et al., 2007) for programming the embedded open MAS because it is a well-explored platform and has a customized agent architecture capable of controlling physical resources named ARGO (Pantoja et al., 2016) to allow programming Physical agents. The Jason has another customized agent architecture capable of communicating using the middleware ContextNet, an agent with this architecture is named *Communicator* (Pantoja et al., 2018). However, the Jason does not have a mechanism to transfer agents.

Therefore, we extend the *Communicator* agent architecture to create Open MAS to send and receive agents from other MAS using the ContextNet. With ARGO and *Communicator* agent extended architecture, it is possible to have multiple Embodied MAS coexisting in the same physical environment connected to a communication infrastructure, characterizing an Embodied MAS ecosystem. When a bio-inspired protocol is activated, the Sender Embodied MAS saves the current mental state (all beliefs, intentions, plans, and goals) of each agent that will be transferred. It creates a file to be transferred and used to initialize these agents in the Receiver Embodied MAS. Finally, the Receiver Embodied MAS identifies the protocol type that must be activated and execute.

In the inquilinism protocol, all agents are transferred, but they are only hosts in the Receiver MAS. They cannot perform any action, and it is only possible to interact with existing agents. In the predation, all Sender MAS' agents are transferred as well; but it dominates the Receiver MAS, and all its native agents are killed, remaining only the agents transferred. In both past protocols, the Sender Embodied MAS is deleted for security and privacy purposes. In the mutualism protocol, one or more agents are moved to another Embodied MAS to learn new skills and then return after the learning process is over. Afterward, independently of the protocol chosen, all agents transferred are instantiated in the Receiver MAS.

To activate the bio inspired protocol, it was developed an internal action — it is an action that an agent can perform that does not affect the environment in Jason framework (Bordini et al., 2007) — named *.moveout*. To perform this internal action is necessary to pass two or three parameters:

- **Identifier:** it is the unique identifier of a *Communicator* agent. This parameter identifies the Embodied MAS that will receive the agents;
- **Ecological Relation:** one of the three ecological relations available that can be used;
- **Agent Name:** it identifies the agents that will be sent. It is an optional parameter that is only used when the mutualism relation is activated. In other relations, all agents are always transferred.

Once the *.moveout* internal action is called, two algorithms are executed. The algorithm 1 is executed by the Sender Embodied MAS receiving the identifier of the *Communicator* agent from the Receiver Embodied MAS, the ecological relation, and the agents' name in case of mutualism. After that, all selected agents are prepared to be sent, preserving their actual mental state (beliefs, plans, intentions, and goals). For this, it accesses the mental state of all agents selected at runtime. Then, it sends these selected agents, and wait for a acknowledgment message. If they were instantiated in the Receiver Embodied MAS correctly, these agents are killed, otherwise, the process is aborted. It is important to remark that kill all selected agents erases the embedded MAS.

Algorithm 1: Algorithm of the MAS who active the bio-inspired protocol (Sender Embodied MAS).

procedure $transferAgents$(idReceiverMAS, ecologicalRelation, [agentName])
  $selectedAgents \leftarrow null$
  if ecologicalRelation = "Predation" or ecologicalRelation = "Inquilinism" **then**
    $selectedAgents \leftarrow getAgents(all)$
  else
    if ecologicalRelation = "Mutualism" **then**
      $selectedAgents \leftarrow getAgents(agentName)$
    end if
  end if
  $sendAgents(idReceiverMAS, ecologicalRelation, selectedAgents)$
  if $transference = OK$ **then**
    $kill(selectedAgents)$
  else
    $abort()$
  end if
end procedure

Considering the Receiver Embodied MAS, the Algorithm 2 starts when the *Communicator* agent detects the ecological relation to be performed, and the agents received. Firstly, the algorithm creates and initializes all the received agents. A message is sent back if all received agents are initialized correctly or not. Then, if the ecological relation is the predation, all existing agents at this moment — that were not transferred by the ecological relation — are killed.

Algorithm 2: Algorithm of the MAS who receive the agents transferred with the bio-inspired protocol.

procedure $receiveAgents$(ecologicalRelation, agentsTransfered)
  $createAndInitialize(agentsTransfered)$
  if ecologicalRelation = "Predation" **then**
    $updateSerialPorts(agentsTransfered)$
    $kill(myAgents - agentsTransfered)$
  end if
end procedure

The Embedded MAS uses ARGO for interfacing and controlling physical resources and to interact with a real environment using a physical body. It must be composed of a microcomputer and one or more microcontroller; the first is used for hosting the Embedded MAS, and the microcontroller is used for connecting electronic components.

A Physical agent using the ARGO can control multiple microcontrollers; it has each microcontroller's serial port for accessing the sensors and actuators. As the serial port is not fixed, it maintains a belief for each serial port. Therefore, before all agents are killed in the Receiver MAS, the transferred ARGO agents update their serial ports using the ports set in the Receiver ARGO agents. When developing MAS in real environments, one must consider the unpredictability and the risks that an Embodied MAS can be exposed to. Agents are continuously learning and it could become critical as time passes by. A mechanism to preserve agents' knowledge becomes essential to MAS in a real environment. Our proposed bio-inspired protocols aim to overcome this situation.

4 FORMALIZATION FOR THE BIO-INSPIRED PROTOCOLS

In this section the ecological relations with its corresponding use with the agents are formalized.

Definition 4.1 (Bio-inspired Protocol). *A Bio-Inspired Protocol (or Bio_TP) is defined by the following 3-tuple:*

$$Bio\_TP = \langle Sender, Receiver, AP \rangle$$

where,

- *Sender is a MAS comprised by the following sets of Agents:*

  $$Sender = \langle PA_S, TA_S, CA_S \rangle$$

  where,

  PA_S is a set of n Physical Agents from the Sender, where $n \geq 0$.

  TA_S is a set of n Traditional Agents from the Sender, where $n \geq 0$.

  CA_S is a set with a single agent named Communicator from the Sender.

- *Receiver is a MAS comprised by the following sets of Agents:*

  $$Receiver = \langle PA_R, TA_R, CA_R \rangle$$

  where,

  PA_R is a set of n Physical Agents from the Receiver, where $n \geq 0$.

  TA_R is a set of n Traditional Agents from the Receiver, where $n \geq 0$.

  CA_R is a set with a single agent named Communicator from the Receiver, responsible for establishing the communication between the Receiver and a given Sender.

- *AP (or Activate Protocol): the third element from the tuple defines which kind of bio-relation will be executed by the protocol; There are three possible kinds: Predation, Inquilinism, and Mutualism. As it follows, we describe these three different protocols executions using set theory formalisation.*

  1. *Predation*

     $PA_R = PA_S - PA_R$; $TA_R = TA_S - TA_R$

     $CA_R = CA_S - CA_R$

     $PA_S = \emptyset$; $TA_S = \emptyset$; $CA_S = \emptyset$

     NB-1: In the Predation relation the Sender takes control over the Receiver. That is the reason we use difference of sets in the first line above. In the third line all three sets are assigned as empty because the agents from the Sender should be removed.

  2. *Inquilinism*

     $PA_R = PA_S \cup PA_R$; $TA_R = TA_S \cup TA_R$

     $CA_R = CA_S \cup CA_R$

     $PA_S = \emptyset$; $TA_S = \emptyset$; $CA_S = \emptyset$

     NB-2: In the Inquilinism all agents from the Sender are merged with agents from the Receiver. That is why we have used union of sets above. Similarly, in the third line (above) all three sets are assigned as empty.

  3. *Mutualism*

     $\{PA_R = PA_S \cup PA_R; PA_S = PA_R \cup PA_S\} \mid PA_R = PA_R$

     $\{TA_R = TA_S \cup TA_R; TA_S = TA_R \cup TA_S\} \mid TA_R = TA_R$

     $CA_R = CA_R$;

     NB-3: In the Mutualism there is an option that could be selected for the new set of PA_R and TA_R, i.e., it may occur a merge of sets (using union of sets) or the Sender's agents may remain in the Sender and they are not transferred to the Receiver. Besides all Sender's agents should be preserved, thus there is no empty set operation. Notice that in case the agents from the Sender have been sent to the Receiver, then at some point, they should be sent back to the Sender. This is represented by the operations placed between brackets.

5 PROTOTYPE: DESIGNING AND TESTING

This section presents the tests and results of the bio-inspired protocols proposed. The tests use the concept of autonomous underwater vehicles for each of the proposed bio-inspired protocols. Autonomous Underwater Vehicles (AUV) (Cruz, 2011) are crewless vehicles with internal processing that autonomously perform actions based on sensors' information. AUV are regularly used to explore the sea's areas where humans cannot go. Considering this, our mechanism for preserving the collected information could become vital. The tests performed in this work show scenarios where each bio-inspired protocol can be applied in an AUV application as an Embodied MAS.

The first scenario is characterized by two Embodied MAS with exactly the same hardware exploring a new sea area. One of these Embodied MAS (Leader) has more important knowledge than the other (Soldier). During the exploration, the Leader's AUV is damaged, and to protect the integrity of its knowledge, it activates the bio-inspired protocol using the predation relation and preys the Soldier. The second scenario the Soldier's AUV is damaged and has more important knowledge than the Leader Embodied MAS. Hence, the Soldier activates the bio-inspired protocol with the inquilinism relation to transfer all its agents to the Leader and remains tenant until another AUV with the same hardware is available to the Soldier control. Since it is the Soldier, and by hierarchy purposes, it cannot prey its Leader. In the third scenario, a new Embodied MAS (Student AUV) is sent on an exploration mission with a more experienced Embodied MAS (Teacher AUV), who knows the most part of the area explored. In this case, the Student activates the bio-inspired protocol with the mutualism relation for sending a group of agents to the Teacher to learn; afterwards, they return to the student MAS with the knowledge acquired to perform a better exploration.

Two prototypes of autonomous vehicles were developed. These vehicles are equals considering the hardware composition, and each one is composed of 1 Raspberry pi zero microcomputer and 1 Arduino Uno. Besides, they employ 1 luminosity sensor (LDR), 1 temperature sensor (LM35), 2 white LEDs, 2 DC 3-6V motors (1 for each wheel), 1 H bridge driver module (L298N), and 2 power banks (one for the microcomputer and the other for the microcontroller). All these components are interconnected in a circuit composed of resistors and capacitors connected to the Arduino Uno. In figure 2 shows the prototypes.

5.1 Test Results

All developed MAS for the test scenarios had versions with different amount of agents — 10, 30, and 50 agents — to check if exists interference in the transfer speed. Besides, we tested the effectiveness

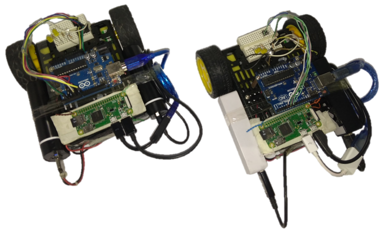

Figure 2: Car prototypes for testing in a real world.

of performing the agents' transferring and checked if the agents' knowledge was preserved. Considering that all agents are always transferred in the predation and inquilinism relations, the tests with mutualism assumed the worst-case transferring all agents.

For each scenario, all MAS versions (10, 30, and 50 agents) were tested 10 times, resulting in 30 tests per scenario and 90 tests combining all three scenarios. Moreover, an internet with 5 Mbps speed was used for the ContextNet middleware to create the communication infrastructure. The Table 2 shows the transfer speed average for each scenario including the ecological relation applied. Finally, the efficiency of transport and knowledge preservation is shown.

Table 2: A comparative table considering the three scenarios.

	Time to complete			
Eco. Rel.	**10 Ag.**	**20 Ag.**	**50 Ag.**	**Eff.**
Predation	0.43 s	0.74 s	1.46 s	100%
Inquilinism	0.39 s	0.70 s	1.03 s	100%
Mutualism	0.38 s	0.69 s	1.03 s	100%

When analyzing the results, we conclude that the number of agents directly interferes with the protocols' execution. When the protocol sends multiples agents to another MAS, it must access the entire base of beliefs, desires, intentions, and plans of each agent to transport. After that, when these agents arrive at the Receiver MAS, they are instantiated individually.

Considering the scenarios and the results, we conclude that the predation is more appropriate when the Embodied MAS hardware is damaged, and it still needs to continue logically operating, not only saving the agents' knowledge because this relation is slower than the others and requires another Embodied MAS with exact the same hardware. The inquilinism suits in cases where the Embodied MAS's hardware is deteriorating, there is no other similar hardware, or there is no need for it to remain operational. The main goal is to preserve the agents' knowledge. This relation is one of the fastest and can be performed independently of the MAS physical configuration.

Finally, the mutualism relation is appropriate for cases where the Embodied MAS needs to learn new knowledge, and when communicating does not apply or is not secure. For example, when installing a new sensor in the AUV scenario, the student MAS sends a physical agent to the teacher MAS to learn with its physical agents. Then, the transferred agent returns with the knowledge to operate the sensor.

6 CONCLUSION

This work presented bio-inspired protocols for Embodied MAS inspired by ecological relations. It shows the importance of preserving the integrity of the agents' knowledge depending on the situation that an Embodied MAS could be exposed to when it is inserted in real environments where maintaining the knowledge can be crucial to the mission's success.

Three protocols based on ecological relations were implemented: Predation, Mutualism, and Inquilinism. In predation, all agents of a MAS is transferred to another MAS to dominate it. In this situation, the Sender MAS has crucial knowledge in a mission; nevertheless, it is physically damaged, then they transfer their agents to a MAS with similar hardware and dominates it. In mutualism, some MAS agents can be transferred to another MAS to learn or exchange knowledge. After that, they can return to the Sender MAS to share the new knowledge acquired during the transference. In Inquilinism, all agents from the Sender MAS are transferred to another MAS to preserve their knowledge without dominating it.

As future work, we aim to implement an ecosystem of Embodied MAS in the computer lab of our university to broaden the testing environment and the number of devices involved. Moreover, a new feature called the dominance degree is being developed. The degree of dominance maps all possible predation relation between Embodied MAS. Thus, an Embodied MAS with less dominance degree can not prey on the other, but the bio-inspired protocol will automatically change the relation to inquilinism if it tries.

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