ID - ASSIGNMENT METHOD FOR MODULAR ROBOTS
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***Abstract*— Modular robots are autonomous systems with variable morphology, composed of independent connected computational elements, called particles or modules. Due to critical resource constraints and limited capabilities, globally unique identifier (ID) assignment to each particle is a very challenging task in modular robots. However, having a unique ID in each one remains essential for various operations and applications in this domain. For instance, it is required to establish communications between nodes and implement routing protocols. It helps in saving energy consumption and enhancing the security mechanisms. In this paper, we propose a distributed unique ID assignment method for modular robots. It is a three phases based algorithm. The first phase consists in discovering the system while building a logical tree. The second phase finds the total size of particles in the system needed for several operations in modular robots, and the third one is dedicated to the unique ID assignment. After fully optimizing the distributed algorithm, the effects of various system shapes and leader positions on the energy and time complexity are studied, while proposing fitting solutions for different requirements.**

I. INTRODUCTION

Modular robots, or modular self-reconfiguring robotic systems, are autonomous systems with variable morphology. These systems are composed of independent connected elements called modules or particles, whose connections to one another form the overall shape of the system. Beyond sensing, processing and communication capabilities, a modular robot includes actuation and motion capabilities that allow it to reconfigure its shape by rearranging connections between modules [20, 9]. A wide range of applications for modular robots reside unexplored [2], from surgical applications, to transportation applications and space exploration. The main tasks of a modular robots system are to reconfigure its shape in order to accommodate for variable conditions that need to be met in order to complete a given final goal, and the ability to read sensing values from anywhere on the system [19]. Both of these tasks rely on message transmission between modules directly connected or connected through other modules. As modular robots are essentially systems with ever-changing shapes, and thus ever-changing modules locations, it is therefore important to have some kind of identification for each module that remains constant throughout all of the modifications the system may go through.

A global unique ID is naturally proposed as a solution for such a requirement. It is required for various operations and applications [5, 12, 16]. Unique IDs are used to establish communications between nodes and to implement routing protocols. It helps in saving energy consumption and enhancing the security mechanisms. Furthermore, globally unique IDs in modular robots are used to find the mapping between two configurations [14] or for self-assembly algorithms [19, 18]. To accomplish this goal one might suggest at the manufacturing level and whenever a module is manufactured to directly assign a global unique ID to it (similar to a MAC on most electronics). However, such an approach is highly inefficient and limiting, as it would impose very long IDs in order for them to be globally unique and would require many extra steps in the manufacturing process (e.g., the ID assignment process and the maintenance of unique IDs between various manufacturers). In addition, modular robots suffer from scarcity of energy, and message passing tasks play an important role in its energy consumption. As information passed between modules is relatively small in size and often aggregated, the message's header containing the origin and destination IDs presents a more weighted role in the message's size, and thus in energy consumption. Therefore, due to the large number of particles it is almost impossible to manually assign a unique ID to each particle. It is up to the particles to assign themselves each a unique ID in a distributed and memory/energy efficient manner. The first and simple technique that comes to mind is a random ID assignment [17]. However, we need very long IDs to ensure a low probability of two particles choosing the same ID which is not suitable for modular robots with low memory and energy resources. An approach is proposed in [7] which considers the k-local identifier problem. In this approach the IDs are presented as variables assigned to each particle of the network, that are different for every two modules at a distance of at most k (k hops). In this case, we do not have long ID at each particle. However, different nodes can have the same ID, and in particular in the same neighborhood. Thus, it is important to uniquely identify the next hop node during message routing. Furthermore, in this situation the matching between two configurations based on particles IDs as described in [14] becomes more complicated or even impossible to be achieved.

A more closely related problem is ID Assignment in Wireless Sensor Networks (WSN) [13, 22, 11, 10, 21, 15, 8]. We can observe that many of the issues and constraints are shared between WSN and modular robots: a large number of nodes, limited memory, processing power and energy, etc. Nevertheless, there are significant differences as well, notably that the topology of modular robots will evolve continuously as the robot changes its morphology. The com-

munications in modular robots are generally done only with the adjacent neighbour modules (i.e., communication through modules borders, as wireless communication is much more costly and prone to errors) [3] which reduces the impact on messages loss. Numerous works have been conducted in the sensor networks field concerning the task of ID assignment; from attribute-based ID assignments, to unique ID assignment and a variable-length ID scheme [11]. For instance, the Self-organized ID Assignment (SIDA) approach has been proposed in [11] that essentially implements a variable-length ID scheme that assigns longer IDs to the nodes the closest to the sink, with the shortest IDs being assigned to the furthest nodes in the system. While the SIDA approach can be very useful in sensor networks, once again due to the variable morphology of the modular robots systems, such an approach would not be beneficial in our use case, and in fact, could have a negative effect on the performance of the system (as modules with long IDs could end up in a very far position from the leader particle). In [13] the authors propose a work to assign unique and static-length IDs to all sensor nodes. A tree structure was built starting from the sink while temporary IDs are assigned in order to find the total number of sensor nodes. Then ID assignment responsibilities were distributed from the sink to the sensor nodes to complete the final ID assignment.

In this paper, we explore the potential for synergy between WSNs and modular robots while focusing on the unique ID assignment task. We aim to develop a distributed algorithm inspired from those proposed in the domain of sensor networks [13, 11] and adapted to modular robots. The goal is to achieve the smallest possible ID length in order to cover all modules and to reduce the number of messages exchanged between particles. Then, it aims to discover the whole system of modules while along the way building a logical tree structure rooted at the leader module and without the need of temporary IDs assignment. This reduces the time complexity of the algorithm. Furthermore, we studied the effects of the different modular robots configurations and the leader's position on the performance of the algorithm in terms of the number of messages exchanged between modules and the time complexity.

The remainder of this paper is organized as follows. In Section II, we develop the distributed algorithm that can be split into three phases: exploration phase, system size reporting phase and unique ID assignment phase. In Section III, discussions on the effect of modular robots properties (system shapes and leader position) on the time and energy complexity are presented, as well as several simulation results. Finally, Section **??** concludes with a brief description of future work.

II. Unique ID Assignment Algorithm

Our distributed ID assignment algorithm could be split into three main phases: exploration phase, system size reporting phase and unique ID assignment phase. In the first phase, and after electing the leader [6, 4], the goal is to discover the whole system of modules while along the way building a tree structure rooted at the leader module. In parallel, the second phase is launched, in which the algorithm will be collecting the system size (i.e., number of modules in the system) with the final goal of reporting the total size from the whole system to the leader module. Having the system size in hand, the leader module can calculate the least amount of bits needed in order to code global unique IDs for every module in the system. In the third phase, and after building the tree structure that logically connects modules and calculating the least amount of bits needed, the final step of unique ID assignment is launched from the leader to the whole system.

A. System assumptions

Several assumptions shall be presented before starting the development of the algorithm:

- The size of the system (i.e., the number of modules) as well as the initial shape of the system are unknown.
- The leader is elected and can be any module in the system and in any position (center, border, etc.). It is elected to "lead" the process of ID assignment.
- All communications are only possible between adjacent neighbour modules; The sender module sends a message through its border n, and the receiving module receives the message from its border m. If a reply message is needed, the receiving module would reply via its border m, which would then be received by the initial sender module via its border n.
- Each module is aware of the connections it has at any given moment (i.e., it is aware which of its borders are connected to other modules, and which borders are free). In this case, we consider that the loss of any message transmitted between the borders of modules is considered to be highly improbable, and thus, not taken into consideration.
- All modules in the system are considered to be alive until the completion of the algorithm and no new modules are introduced during the execution. However we plan on relaxing the latter assumption in our future work.

B. Phase 1: Exploration

This phase's goal is to discover the whole system of modules, while building a logical tree structure rooted at the leader module along the way. The algorithm starts with the initiation from the leader module and by using 3 types of messages. Type 1, 2 and 3 messages are all that is needed to discover and create a tree structure for the system (cf. Table I). Type 1 messages represent potentially discovering new modules; type 2 messages are confirmations that a new module has been discovered and it is one of the children of the sender module; and type 3 messages reply by neglecting the fact that a module is to be discovered, and notify the sender module that the destination module is already discovered. Also, to notice that type 2 messages are the only way to expand the tree structure of the system.

The leader module starts by specifying that it is now discovered, and that it has no parent (as it is the root node

TABLE I

MESSAGES' ROLE DESCRIPTION

Type	Role Description
1	Explore neighbours for potential children
2	Confirm that the explored node is a child
3	Decline that the explored node is a child
4	Report the node's sub-tree size to its parent
5	Distribute the global unique IDs to children

in the tree), and would finally transmit type 1 messages to each of its neighbours. Whenever a module receives a type 1 message, two cases are possible. The first case, if it is the first time it receives a type 1 message it initializes its parent to be the sender module. It then replies back by a type 2 message which notifies the parent that this node is now one of its children. Finally, it proceeds by sending type 1 messages to its own neighbours (excluding the already known to be parent neighbour). The second case, if it is not the first time that it receives a type 1 message (the module is already discovered by another module) it sends back a reply message of type 3, which notifies the sender module that this module is not its child. The Algorithm's part concerning the first phase is presented in algorithm - phase 1.

Global Unique ID Assignment Algorithm - Phase 1

```
is_discovered ← false
leader ← false
parent ← −1
unique_id ← −1
neighbours ← ∅
children ← ∅

if leader = true AND is_discovered = false then
  is_discovered ← true;
  for each neighbour in neighbours do
    send type 1 message to neighbour
  end for
end if

if received message then
  switch message.type do
    case 1
      if is_discovered = true then
        send type 3 message to message.origin
      else
        is_discovered ← true
        parent ← message.origin
        neighbours ← neighbours − {message.origin}
        send type 2 message to message.origin
        for each neighbour in neighbours do
          send type 1 message to neighbour
        end for
      end if
    case 2
      neighbours ← neighbours − {message.origin}
      children ← children ∪ {< message.origin, −1 >}
    case 3
      neighbours ← neighbours − {message.origin}
end if
```

An illustration example is presented in Figure 1. In this example, and in further illustrations and results, we will utilize the use case of a square module, having 4 borders. In Figure 1, the light grey box represents the leader module, medium grey boxes represent discovered modules, and black boxes represent the absence of a module. At stage 1, all modules are yet to be discovered and the leader module is selected. In stage 2, the leader module initiates phase 1 of the algorithm by sending type 1 messages to its neighbours. In stage 3, as all modules are not yet discovered and it is the first time that they receive a type 1 message, all four neighbours reply by a type 2 message to the leader module. This informs the leader module that all four of its neighbours are its children. In stage 4, the newly discovered modules now try to discover in their turn their neighbours, via type 1 messages. In stage 5, we can observe that the module to the left of the leader won the race in discovering the new module, and receives a type 2 message confirming this fact. Whereas the module under the leader receives a type 3 message, meaning that the module is already discovered. This process keeps on repeating until all modules in the system are discovered. Modules that already received all replies from their neighbours or don't have neighbours left to discover (i.e., their only neighbour is their parent) are ready to start phase 2.

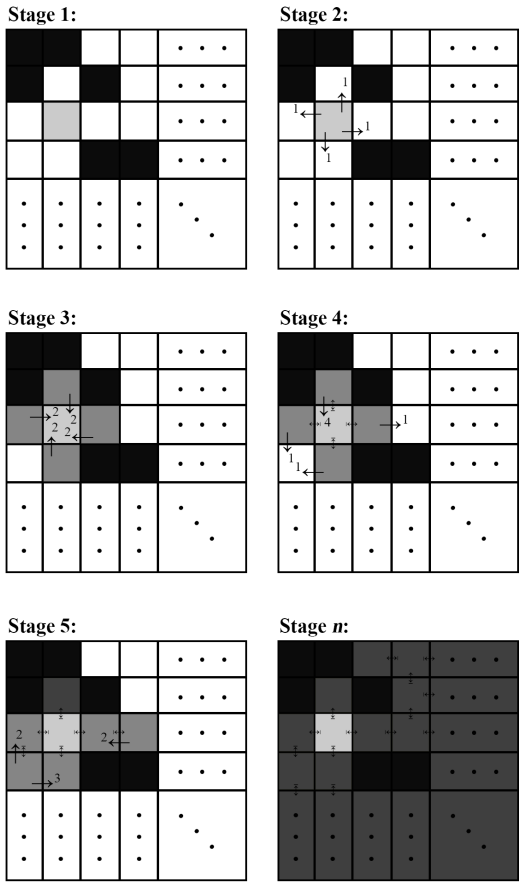

Fig. 1. Illustration of an example of the 5 first stages in Phase 1 and 2, as well as the final stage n reached at the end of those phases.

C. Phase 2: System Size Reporting

In this phase, that is run in parallel with the previous phase, the main idea is that whenever a module is discovered and all

of its subsequent children finish discovering their respective sub-trees (or if this module doesn't have any children), this module should report its own sub-tree size to its parent. The sub-tree size of a given module is the size of the tree structure that is rooted at this module. Thus, this process of sub-tree sizes reporting will emerge from the leafs to the leader module.

Type 4 messages are now introduced (cf Table I). These messages are only passed from child to parent and they carry out an integer value named "sub-tree_size" that represents the sub-tree size of the child node.

After a module has been discovered, and it has sent out type 1 messages to all of its neighbours (potential children) and it received back all reply messages (either type 2 or type 3), it would: If all neighbours replied with type 3 messages or if it has no neighbours other than its parent (both cases represent the case of a leaf) → send a type 4 message to its parent, with value 1. If one or more neighbours replied with a type 2 message (i.e., the node has at least one child) → wait for all children to send their sub-tree sizes, and only when they do, proceed by sending a type 4 message to its own parent, which now carries its own sub-tree size that is the sum of all sub-tree sizes received from its children + 1 (plus itself). This process keeps on repeating until eventually all sub-tree sizes would be transmitted from child to parent and the leader module would receive the final total system size (the sum of its direct children sub-tree sizes + 1). The Algorithm's part concerning the second phase is presented in algorithm - phase 2.

Continuing and expanding on the illustration example in Figure 1, medium grey boxes represent more precisely discovered modules that did not send their sub-tree size, while dark grey boxes represent modules that have been discovered and have sent their sub-tree size to their respective parent. In stage 4, and as the module above the leader has no neighbours to discover, this module directly proceed to phase 2 by reporting its sub-tree size (that is 1) to its parent (the leader module). In stage 5 the leader module receives the sub-tree size of the module above it, rendering the module above it in the dark grey state, meaning it has finished its tasks for phases 1 and 2. This process keeps on repeating, until all modules are in the dark grey state, and the total system size is reported to the leader (stage n). Having such information available, the leader calculates the least amount of bits needed to code globally unique IDs for the whole system and is thus ready for the ID assignment phase. This state of the algorithm represents the end of phases 1 and 2.

Global Unique ID Assignment Algorithm - Phase 2

```
subtree_size ← 1
subtree_size_sent ← false

if received message then
  switch message.type do
    case 1
      if is_discovered = true then
        ...
      else
        ...
        if neighbours.size = 0 AND !subtree_size_sent then
          CHECK( )
        else
          for each neighbour in neighbours do
            send type 1 message to neighbour
          end for
        end if
      end if
    case 2
      ...
    case 3
      ...
      if neighbours.size = 0 AND !subtree_size_sent then
        CHECK( )
      end if
    case 4
      child ← find message.origin in children
      child.subtree_size ← message.subtree_size
      subtree_size += message.subtree_size
      if neighbours.size = 0 AND !subtree_size_sent then
        CHECK( )
      end if
end if

procedure CHECK( )
  if children.size = 0 OR received all children subtree_size then
    if leader = false then
      send type 4 message to parent
      subtree_size_sent ← true
    else
      calculate least necessary bits
      ...
    end if
  end if
end procedure
```

D. Phase 3: Unique ID Assignment

This phase's goal is to distribute the globally unique IDs (all coded with the same number of bits) to all modules of the system. After the calculation of the least amount of bits needed, the leader module proceed by assigning the ID 0 to itself, and sending IDs to its children via type 5 messages (cf Table I). When a module receives a type 5 message, it assigns the ID number in this message as its unique ID and proceed by sending type 5 messages to its children (if it has any). The sending of type 5 messages to children should respect the following: (i) send the module's ID + 1 to the first child, (ii) send the module's ID + 1 + $\sum_{n=1}^{i-1} S_n$ to the i^{th} child, where S_n is the sub-tree size of the n^{th} child. This assures that whenever a module receives an ID via a type 5 message, the range of IDs going from its own ID to its ID + its sub-tree size, is reserved for it and for its sub-tree.

An illustration example of the execution of this phase is presented in Figure 2, where white boxes now represent modules that finished their execution. Supposing that the module to the left of the leader has a sub-tree size of 9, the leader would send the ID 0 + 1 (i.e., its own ID + 1) to it, while sending the ID 0 + 1 + 9 = 10 to the module too its right. This reserves all IDs from 1 till 9 to the sub-tree of the module to the left of the leader. The same principle applies supposing that the right module has a sub-tree size of 87, the ID 0 + 1 + 9 + 87 = 97 will be sent to the third and last child of the leader. This process keeps on repeating from parent to child until all modules in the system receive their globally unique IDs. The Algorithm's part concerning

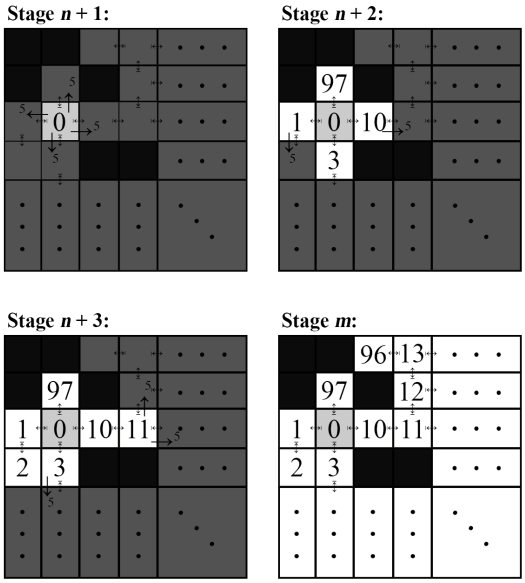

Fig. 2. Illustration of the first three stages of phase 3, plus the final stage m of the system after the completion of the algorithm.

the third phase is presented in algorithm - phase 3.

Global Unique ID Assignment Algorithm - Phase 3

```
if received message then
  switch message.type do
    case 1
      ...
    case 2
      ...
    case 3
      ...
    case 4
      ...
    case 5
      final_id ← message.id
      next_id ← message.id + 1
      for each child in children do
        send type 5 message to child
        next_id += child.subtree_size
      end for
end if

procedure CHECK( )
  if children.size = 0 OR received all children subtree_size then
    if leader = false then
      ...
    else
      calculate least necessary bits
      unique_id ← 0
      next_id ← 1
      for each child in children do
        send type 5 message to child
        next_id += child.subtree_size
      end for
    end if
  end if
end procedure
```

III. Work to do : Analysis study and numerical results

In this work, you should study the impact of the modular robots' initial properties on the performance of the proposed algorithm, mainly the initial system shape and the position of the leader.

The algorithm must be implemented in VisibleSim [1], simulator dedicated to modular robots.

The complexity of this algorithm is affected by the number of neighbours which is largely related to the shape of the system. Next you should develop and test three cases of initial system shapes: filled shape, chain shape, random shape as shown in Figures 3 4 5. Throughout your development, you should compare the simulated time execution and number of exchanged messages for each system shape, for system sizes ranging from 100 modules to 40,000 modules.

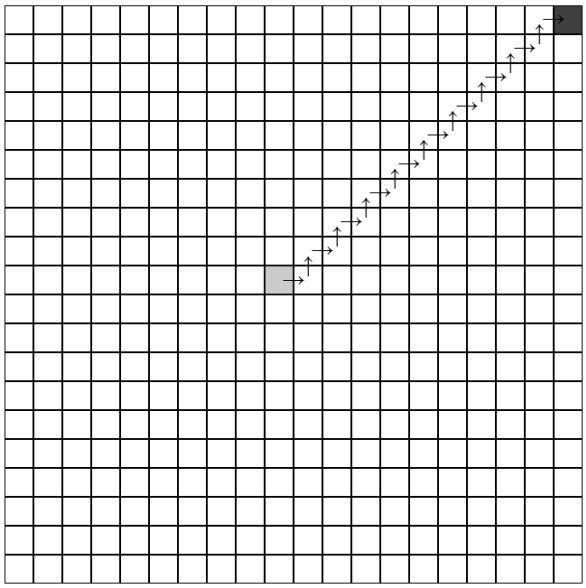

Fig. 3. Filled shape system example: square

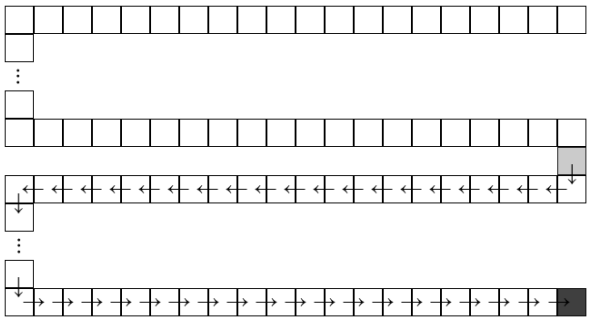

Fig. 4. Chain shaped system example: snake

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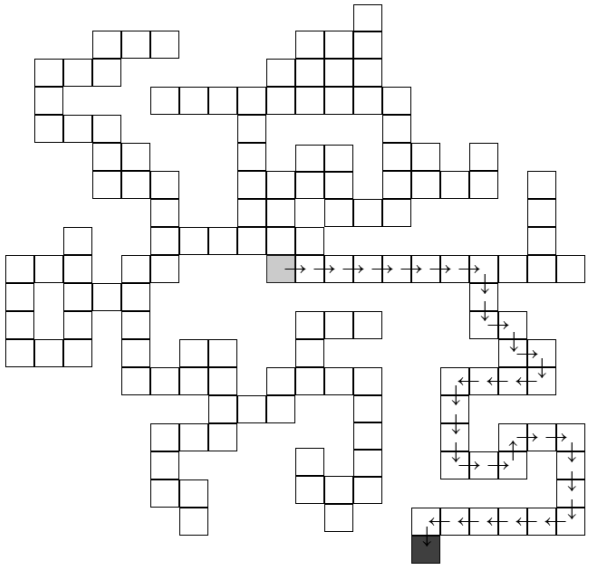

Fig. 5. Randomly shaped system example

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