Buzz: An Extensible Programming Language for Self-Organizing Heterogeneous Robot Swarms

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Abstract—We present Buzz, a novel programming language for heterogeneous robot swarms. Buzz advocates a compositional approach, offering primitives to define swarm behaviors both from the perspective of the single robot and of the overall swarm. Single-robot primitives include robot-specific instructions and manipulation of neighborhood data. Swarm-based primitives allow for the dynamic management of robot teams, and for sharing information globally across the swarm. Self-organization stems from the completely decentralized mechanisms upon which the Buzz run-time platform is based. The language can be extended to add new primitives (thus supporting heterogeneous robot swarms), and its run-time platform is designed to be laid on top of other frameworks, such as Robot Operating System. We showcase the capabilities of Buzz by providing code examples, and analyze scalability and robustness of the run-time platform through realistic simulated experiments with representative swarm algorithms.

Index Terms—distributed robot systems, control architectures and programming, swarm robotics, swarm engineering

I. INTRODUCTION

SWARM robotics systems [1] are envisioned for large-scale application scenarios that require reliable, scalable, and autonomous behaviors. Among the many hurdles towards real-world deployment of swarm robotics systems, one of the most important is the lack of dedicated tools, especially regarding software [2]. In particular, one problem that has received little attention in the literature is programmability. The current practice of swarm behavior development typically focuses on individual behaviors and low-level interactions [3]. This approach forces developers to constantly ‘reinvent the wheel’ to fit well-known algorithms into new applications, resulting in a slow and error-prone development process.

To promote code reuse, two general approaches are possible. The first approach is the development of software libraries that encapsulate certain algorithms. While this has the advantage of leveraging pre-existing frameworks and tools, it falls short of screening the user from unnecessary detail, such as non-trivial compilation configuration or language-specific boilerplate.

The second approach is the creation of a domain-specific language (DSL) exposing only the relevant aspects of the problem to solve. A well-designed DSL shapes the way a system is conceived, by offering powerful abstractions expressed through concise constructs.

In this paper, we argue that a DSL is an indispensable tool towards the deployment of real-world robot swarms. The dynamics of robot swarms are made complex by the presence of both spatial aspects (body shape, sensing, actuation) and networks aspects (message loss, volatile topology). Additionally, to render the production of large-scale swarms affordable, the robots suffer from significant limitations in terms of computational power, especially when compared with robots designed to act alone. Thus, a DSL for robot swarms has the potential to act as a platform that (i) Filters the low-level details concerning space and networking, in an efficient, resource-aware fashion; (ii) Offers a coherent abstraction of the system; (iii) Acts as common platform for code reuse and benchmarking.

In this paper, we present Buzz, a novel DSL for robot swarms. To drive the design of Buzz, we identified key requirements a successful programming language for swarm robotics must meet.

First, as mentioned, the language must allow the programmer to work at a suitable level of abstraction. The complexity of concentrating on individual robots and their interactions, i.e., a bottom-up approach, increases steeply with the size of the swarm. Conversely, a purely top-down approach, i.e., focused on the behaviour of the swarm as a whole, might lack expressive power to fine-tune specific robot behaviors. We believe that a language for robot swarms must combine both bottom-up and top-down primitives, allowing the developer to pick the most comfortable level of abstraction to express a swarm algorithm.

Second, the language must enable a compositional approach, by providing predictable primitives that can be combined intuitively into more complex algorithms and constructs.

Third, the language must prove generic enough to (i) express the most common algorithms for swarm coordination, such as flocking, task allocation, and collective decision making; and (ii) support heterogeneous swarms.

Fourth, the run-time platform of the language must ensure acceptable levels of scalability (for increasing swarm sizes) and robustness (in case of temporary communication issues). Currently, the management of the low-level aspects and corner cases concerning these issues constitutes a sizable portion of the development process of swarm behaviors. Alleviating this burden with a scalable and robust run-time platform is crucial for real-world deployment of swarm behaviors.

The main contribution of this paper is the design and implementation of Buzz, a programming language that meets the requirements discussed above. Buzz is released as open-source software under the MIT license. It can be downloaded at http://the.swarming.buzz/.

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The text is organized as follows. In Sec. II we present the design principles we followed. In Sec. III we introduce the Buzz syntax. In Sec. IV we illustrate the run-time platform. In Sec. V we report a number of scripts meant to showcase the capabilities of Buzz, in particular its conciseness and generality. In Sec. VI we analyze the scalability and robustness of the Buzz run-time. In Sec. VII we discuss related work, outlining similarities and differences of Buzz with respect to existing languages and frameworks. Finally, in Sec. VIII we draw concluding remarks.

II. DESIGN PRINCIPLES

The design of Buzz was based on a set of high-level principles, that are described in the following.

Discrete swarm, step-wise execution. A swarm is considered as a discrete collection of devices, each running the Buzz virtual machine (BVM), and executing the same Buzz script. Script execution proceeds independently on each robot in a step-wise fashion. Each time-step is divided in five phases: 1) Sensor readings are collected and stored in the BVM; 2) Incoming messages are collected and processed by the BVM; 3) A portion of the Buzz script is executed; 4) The messages in the BVM output queue are sent (as many as possible, according to the available payload size; see Sec. IV); 5) Actuator values are collected from the BVM state and applied. The length of a time-step is constant over the lifetime of the script, although it does not need to be the same for every robot. If the execution time of a step is shorter than the allotted time, the robot sleeps for a period. If the execution is longer, a warning message is printed on the screen and the execution proceeds.

Predictable and composable syntax. Buzz employs a simple, imperative syntax inspired by languages such as Python, Lua, and JavaScript. While this syntax ensures a short learning curve, it also allows for predictable and composable scripts. By predictable, we mean that a programmer can easily infer the results of the execution of a program by reading its code. Composability refers to the ability to structure a complex program into simpler elements, such as functions, classes, etc. that can later be used as modules.

Support for heterogeneous robots. Buzz is explicitly designed to support heterogeneous robot swarms. To this aim, Buzz is conceived as an extension language, that is, a language that exports and enhances the capabilities of an already existing system. This design choice allows one to stack the Buzz run-time on top of well-known single-robot frameworks such as ROS, OROCOS, or YARP. The Buzz syntax and primitives are minimal, concise, and powerful; the programmer can add new primitives and constructs that link to relevant features of the underlying system.

Swarm-level abstraction. One of the novel aspects of Buzz is the ability to manage swarms of robots. The concept of swarm is a first-class language object. Swarms can be created and disbanded; new swarms can be created as a result of an operation of intersection, union, or difference between two pre-existing swarms. Each swarm can be atomically assigned operations to perform. Swarms can be employed to encode complex task coordination strategies.

Situated communication. Each robot is assumed to be equipped with a device capable of situated communication. Such device broadcasts messages within a limited range and receives messages from neighboring robots in direct, unobstructed line-of-sight. Upon receipt of a message, a robot also detects the relative distance and angle of the message sender. Situated communication has been used extensively in swarm robotics to achieve global coordination in algorithms for, e.g., pattern formation, flocking, exploration, and task allocation. This communication modality can be achieved on-hardware with robots such as the Kilobot, the e-puck, and the marXbot, although with limited payload size, and a dedicated module for low-cost 3D communication was proposed in [13]. Alternatively, situated communication can be satisfactorily realized through WiFi and GPS (for outdoor scenarios) or tracking systems such as Vicon (for indoor scenarios).

Information sharing. Buzz provides two ways for robots to share information: virtual stigmergy and neighbor queries. Virtual stigmergy is a data structure that allows the robots in a swarm to globally agree on the values of a set of variables. From an abstract point of view, virtual stigmergy is akin to a distributed key-value storage. Among its many potential applications, this structure may be employed to coordinate task execution, e.g., mark the tasks that have already been completed and/or share progress on the uncompleted ones. Neighbor queries allow a robot to inquire its direct neighbors on the value of a certain variable. Upon receiving a request, the neighbors reply with the current value of the variable; these replies are then collected into a list by the robot who requested the data. Neighbor queries are useful when robots must perform local data aggregation, such as calculating averages or constructing spatial gradients.

III. LANGUAGE DEFINITION

A. Robot-wise operations and primitive types

The simplest operations available in Buzz are robot-wise operations. These operations are executed by every robot individually. Assignments, arithmetic operations, loops and branches fall into this category. E.g.:

```plaintext
# Assignment and arithmetic operation
a = 3 + 7

# Loop
i = 0; while(i < a) i = i + 1

# Branching
if(a == 10) i = 0
```

Buzz is a dynamically typed language that offers the following types: nil, integer, floating-point, string, table, closure, swarm, and virtual stigmergy. The nil, integer, floating-point, and string types work analogously to other scripting languages such as Python or Lua. The swarm and virtual stigmergy types are introduced in Sec. III-B and III-D, respectively.

Tables are the only structured type available in Buzz, and they are inspired by the analogous construct in Lua. Tables can be used as arrays or dictionaries.
Buzz also supports functions as first-class objects, implemented as closures [16]. Two types of closures exist: native closures and C closures. Native closures refer to functions defined within a Buzz script, while C closures refer to C functions registered into the BVM (see Sec. [IV-F]).

The combination of tables and closures allows for the creation of class-like structures. Following the object-oriented programming jargon, we refer to functions assigned to table elements as methods:

```buzz
# Create empty table
t = {}  
# Add method to table
x = t.m(6)  
# Add attribute to table
t.a = 4  
# Method call
x = t.m(6)  
# Index syntax, use as array
t[6] = 5  
# Dot syntax, use as dictionary
b = t["b"] = 10
```

B. Swarm management

Buzz lets the programmer subdivide the robots into multiple teams. In Buzz parlance, each team is called a swarm. Buzz treats swarms as first-class objects. To create a swarm, the programmer must provide a unique identifier, which is known and shared by all the robots in the created swarm. The returned value is a class-like structure of type swarm.

```buzz
# Creation of a swarm with identifier 1
s = swarm.create(1)
```

Once a swarm is created, it is initially empty. To have robots join a swarm, two methods are available: select() and join(). With the former, the programmer can specify a condition, evaluated by each robot individually, for joining a swarm; with the latter, a robot joins a swarm unconditionally. To leave a swarm, Buzz offers the analogous methods unselect() and leave(). A robot can check whether it belongs to a swarm through the method in().

```bash
# Check whether a robot belongs to s
if(s.in()) { ... }
```

Once a swarm is created, it is possible to assign tasks to it through the method exec(). This method accepts a closure as parameter.

```javascript
# Assigning a task to a swarm
s.exec(function() { ... })
```

Internally, the closure is executed as a swarm function call. This call modality differs from normal closure calls in that the current swarm id is pushed onto a dedicated swarm stack. Upon return from a swarm function call, the swarm stack is popped. When the swarm stack is non-empty, the swarm.id() method is defined. If called without arguments, it returns the swarm id at the top of the swarm stack (i.e., the current swarm id); if passed an integer argument n > 0, it returns the n-th element in the swarm stack. Besides making the swarm.id() command possible, the swarm stack is instrumental for neighbor operations (see Sec. [IV-D]).

The programmer can create new swarms that result from operations on pre-existing swarms. Four such operations are available: intersection, union, difference, and negation. The first three operations act on two swarms:

```bash
# Create new swarm with robots belonging to both a and b
s = swarm.union(a, b)  
# The first argument is a unique swarm identifier
s = swarm.union(101, a, b)  
# Create new swarm with robots belonging to a or b
s = swarm.union(100, a, b)  
# a, b are swarms defined earlier in the script
```

The fourth operation, negation, is encoded in the others() method and it creates a new swarm that contains all the robots that do not belong to a given swarm:

```bash
# Create a new swarm n as the negation of swarm s
n = s.others(123)
```

C. Neighbor operations

Buzz offers a rich set of operations based on the neighborhood of a robot. These operations include both spatial and communication aspects.

The neighbors structure. The entry point of all neighbor operations is the neighbors structure. For each robot, this structure stores spatial information on the neighbors within communication range. The structure is updated at each time step. It is internally organized as a dictionary, in which the index is the id of the neighbor and the data entry is a tuple (distance, azimuth, elevation).

Iteration, transformation, reduction. The neighbors structure admits three basic operations: iteration, transformation, and reduction. Iteration, encoded in the method foreach(), allows the programmer to apply a function without return value to each neighbor. For instance, to print the data stored for each neighbor, one could write:

```bash
# Iteration example (rid is the neighbor's id)
neighbors.foreach(
  function(rid, data) {
    print("robot ", rid, ": ",
    "distance = ", data.distance, ", ",
```
Transformation, encoded in the method `map()`, applies a function with return value to each neighbor. The return value is the result of an operation on the data associated to a neighbor. The end result of mapping is a new `neighbors` structure, in which each neighbor id is associated to the transformed data entries. For example, to transform the neighbor data into cartesian coordinates, one could proceed as follows:

```javascript
function(rid, data) {
  var c = {};
  c.x = data.distance * math.cos(data.elevation) * math.cos(data.azimuth);
  c.y = data.distance * math.cos(data.elevation) * math.sin(data.azimuth);
  c.z = data.distance * math.sin(data.elevation);
  return c;
}
```

Reduction, encoded in the method `reduce()`, applies a function to each neighbor to produce a single result. For instance, this code sums the cartesian vectors calculated in the previous example:

```javascript
result = cart.reduce(function(rid, data, accum) {
  accum.x = accum.x + data.x;
  accum.y = accum.y + data.y;
  accum.z = accum.z + data.z;
  return accum;
}, { x=0, y=0, z=0 });
```

Filtering. It is often useful to apply the presented operations to a subset of neighbors. The `filter()` method allows the programmer to apply a predicate to each neighbor. The end result of the `filter()` method is a new `neighbors` structure storing the neighbors for which the predicate (a function) was true. For instance, to filter the neighbors whose distance is within 1 m from a robot, one could write:

```javascript
onemeter = neighbors.filter(function(rid, data) {
  # We assume the distance is expressed in centimeters
  return data.distance < 100;
});
```

Another common necessity is filtering neighbors by their membership to a swarm. The `kin()` method returns a `neighbors` structure that contains the robots that belong to the same top-of-the-stack swarm as the current robot. The `nonkin()` method returns the complementary structure. An example application for these methods is offered in Sec. IV.

Communication. Another use for the `neighbors` structure is to exchange and analyze local data. To make this possible, Buzz offers two methods: `broadcast()` and `listen()`. The former allows the robot to broadcast a `(key, value)` pair across its neighborhood. The latter takes two inputs: the `key` to listen to, and a `listener` function to execute upon receiving a value from a neighbor. The BVM executes the `listener` whenever data is received until the method `neighbors.ignore(key)` is called. As an example, in Sec. IV we report an experiment in which a robot swarm forms a distance gradient from a robot acting as source.

D. Virtual stigmergy

Virtual stigmergy is a data structure that allows a swarm of robots to share data globally. Essentially, virtual stigmergy works as a distributed tuple space analogous to Linda [17]. Three methods are available: `create()`, `put()`, and `get()`. As the names suggest, `create()` is a method that creates a new virtual stigmergy structure, while `put()` and `get()` access the structure, writing or reading `(key, value)` entries.

A virtual stigmergy structure can handle only a subset of the primitives types: integer, floating-point, string, and table. These types can be used either as keys or values.

The name virtual stigmergy derives from the indirect, environment-mediated communication of nest-building insects such as ants and termites [18]. The key idea in natural stigmergy is that environmental modifications to organize the environment occur in a step-wise fashion, whereby a modification performed by an individual causes a behavioral response in another individual, without the two individuals ever directly interacting. From the point of view of the programmer, virtual stigmergy works as a virtual shared environment: a robot modifies an entry, and this modification triggers a reaction in another robot without the two having to interact directly.

As shown in Sec. IV virtual stigmergy is a powerful concept that enables the implementation of a large class of swarm behaviors.

IV. Run-Time Platform

A. The Buzz virtual machine

The run-time platform of Buzz is based on a custom, stack-based virtual machine written entirely in C. The organization of the modules composing the VM is depicted in Fig. 1. The implementation of a new VM is motivated by the design choices in Buzz. In particular, the integration of swarm management and virtual stigmergy into a VM for a dynamically-typed, extensible language forced us to find dedicated solutions for data representation, stack/heap management, and byte code encoding. The specifics on these aspects are purely technical and go beyond the scope of this paper. A notable fact about the BVM is its tiny size (12 KB) which fits most robots currently in use for swarm robotics research.

At each time step, the BVM state is updated with the latest sensor readings. Sensor readings are typically stored in the heap as data structures (e.g., tables). Incoming messages are then inserted in the BVM, which proceeds to unmarshal them and update the relevant modules. Subsequently, the interpreter is called to execute a portion of the script. At the end of this phase, the updated actuator data is read from the BVM heap and part of the messages in the outbound queue are sent by the underlying system.
C. Swarm management

The management of swarm information is performed transparently by the BVM. Essentially, each robot maintains two data structures about swarms: the first structure concerns the swarms of which the robot is a member; the second stores data regarding neighboring robots. The membership management mechanisms are loosely inspired by CYCLON [19].

Membership management. Every time a swarm.create() command is executed, the BVM stores the identifier of the created swarm into a dedicated hash table, along with a flag encoding whether the robot is a member of the swarm (1) or not (0). Upon joining a swarm, the BVM sets the flag corresponding to the swarm to 1 and queues a message <SWARM_JOIN, robot_id, swarm_id>. Analogously, when a robot leaves a swarm, the BVM sets the corresponding flag to 0 and queues a message <SWARM_LEAVE, robot_id, swarm_id>. Because leaving and joining swarms is not a particularly frequent operation, and motion constantly changes the neighborhood of a robot, it is likely for a robot to encounter a neighbor for which no information is available. To maintain everybody’s information up-to-date, the BVM periodically queues a message <SWARM_LIST, robot_id, swarm_id_list> containing the complete list of swarms to which the robot belongs. The frequency of this message is chosen by the developer when configuring the BVM installed on a robot.

Neighbor swarm data. The BVM stores the information in a hash map indexed by robot id. Each element of the hash map is a (swarm_id_list, age) pair where swarm_id_list corresponds the list of swarms of which the robot is a member, and age is a counter of the time steps since the last reception of a swarm update. Upon receipt of a swarm-related message (i.e., SWARM_JOIN, SWARM_LEAVE, SWARM_LIST), the BVM updates the information on a robot accordingly and zeroes the age of the entry. This counter is employed to forget information on robots from which no message has been received in a predefined period. When the counter exceeds a threshold decided when configuring the BVM, the information on the corresponding robot is removed from the structure. This simple mechanism allows the robots to commit memory storage on active, nearby robots while avoiding waste of resources on unnecessary robots, such as out-of-range or damaged robots. In addition, this mechanism prevents excessive memory usage when the swarm size increases.

Message queue optimizations. To minimize the bandwidth required for swarm management, the BVM performs a number of optimizations on the queue of swarm-related outbound messages.

- If a SWARM_LIST message is queued, the information contained in the message is more up-to-date than any other message in the queue. Thus, all the queued messages are removed and only the latest SWARM_LIST message is kept.
- If a SWARM_JOIN message is queued, three situations can occur: (i) The queue does not contain any message regarding the same swarm id; (ii) The queue contains an older SWARM_LIST message; or (iii) The queue contains an older SWARM_LEAVE message for the same swarm id. In the first case, the SWARM_JOIN message is kept in the queue. In the second case, the SWARM_JOIN message is dropped, the SWARM_LIST message is kept in the queue, and the swarm id of the SWARM_JOIN message is added to the list if not already present. In the third case, the SWARM_LEAVE message is dropped and the SWARM_JOIN message is kept in the queue.
- If a SWARM_LEAVE message is queued, three situations can occur: (i) The queue does not contain any message

If an older SWARM_JOIN message for the same swarm id is present, the new message is discarded.

```
aerial = swarm.create(1)
aerial.select(fly_to)
```

B. Code Compilation

The compilation of a Buzz script involves two tools: a compiler called buzzc and an assembler/linker called buzzasm. The former is a classical recursive descent parser that generates an annotated object file in a single pass. The latter parses the object file, performs the linking phase, and generates the byte code. The compilation process is typically performed on the programmer’s machine, and the generated byte code is then uploaded on the robots.

Because Buzz is an extension language, it is likely for the compiler to encounter unknown symbols. This typically occurs when robots with different capabilities are employed. For instance, flying robots may provide a fly_to() command for motion, while wheeled robots may provide a set_wheels() command (see also Sec. [IV-F]).

By default, the compiler treats unknown symbols as global symbols. Only at run-time, when a symbol is accessed, its actual value is retrieved. In case the symbol is unknown at run-time, its value is set to nil. This mechanism provides a flexible way to write scripts that can work on robots with diverse capabilities. As a simple example, to create a swarm that contains all the flying robots, it is enough to write:

---

Fig. 1. The structure of the Buzz virtual machine.
regarding the same swarm id; (ii) The queue contains an older SWARM_LIST message; or (iii) The queue contains an older SWARM_JOIN message for the same swarm id. In the first case, the SWARM_LEAVE message is kept in the queue. In the second case, the SWARM_LEAVE message is dropped, the SWARM_LIST message is kept in the queue, and the swarm id of the SWARM_LEAVE message is removed from the list if present. In the third case, the SWARM_JOIN message is dropped and the SWARM_LEAVE message is kept in the queue.

D. Neighbor operations

Neighbor operations involve the collection and manipulation of data about nearby robots.

Neighbor data handling. Neighbor information is stored in a sparse array indexed by the robot id of a neighbor. Each entry is a tuple containing the id of the neighbor, its distance, azimuth, and elevation angles expressed with respect to the robot’s frame of reference.

Neighbor data collection. Data collection involves the use of situated communication devices, as discussed in Sec. II. At each time step, a robot broadcasts a message <robot_id>. Upon receiving this message, neighboring robots use their situated communication devices to detect the distance, azimuth and elevation of the sending robot. The neighbors structure is cleared and reconstructed at each time step, to ensure that the data is constantly up-to-date. This operation is not expensive, because typically the number of neighbors of a robot is lower than 10.

Neighbor queries. Neighbor queries allow robots to inquire and share information on the value of a specific symbol. When a robot executes the command neighbors.listen(key, listener), the BVM stores the passed listener in a map indexed by key. Whenever the robot processes a message identified by key, the BVM executes the corresponding listener. The command neighbors.ignore(key) removes listener from the map. The method neighbors.broadcast(key, value) queues a message <key, value>. If a message with the same key is already present in the output queue, the BVM keeps the most recent one.

E. Virtual stigmergy

Virtual stigmergy structures are stored by the BVM in a sparse array indexed by the id provided in the Buzz script. Each entry of the sparse array is a separate virtual stigmergy structure. Internally, a virtual stigmergy structure is a hash map that stores tuples (key, value, timestamp, robot_id) where key is a Buzz primitive type that identifies the entry, value is a primitive type that contains the value of the entry, timestamp is a Lamport clock \[20\] used to impose a temporal ordering on the entry updates, and robot_id is the id of the robot that last changed the entry.

Writing into a virtual stigmergy structure. When a robot writes a new value into a virtual stigmergy structure, the BVM first creates or updates the local entry in the hash map. Subsequently, the BVM queues a message <VSTIG_PUT, vstig_id, key, value, timestamp, robot_id>. Nearby robots, upon receipt of the message, check whether its timestamp is higher than the locally known one. If this is the case, the robots propagate the message. Otherwise, they ignore it. It might happen that two robots advertise an update on the same key with the same timestamp. When this happens, a user-defined conflict-solver function is called. This function is given the conflicting entries as parameters, and must return an entry as result. The resulting entry can be either picked as-is from the input ones, or be a newly created one. To help resolve conflicts, each input entry also contains a robot_id field storing the robot id that generated the entry. If no conflict solver is specified by the user, the entry with the highest robot id is propagated. A further user-defined function is executed by the robot that lost the conflict. By default, this function does nothing; however, in some applications a robot might need to react, e.g. retry sending its update. An example usage of these functions is reported in Sec. V-B.

Reading from a virtual stigmergy structure. When a robot R1 reads a value from a virtual stigmergy structure, the locally known value is returned by the BVM. Subsequently, the BVM queues a message <VSTIG_GET, vstig_id, key, value1, timestamp1, robot_id1> to inquire nearby robots on whether the local entry is up-to-date or not. Upon receiving this message, a robot R2 checks its internal data structure. If R2 knows more up-to-date information, it replies with a message <VSTIG_PUT, vstig_id, key, value2, timestamp2, robot_id2> containing its local version of the entry. If, instead, R2 possesses older information, its BVM updates the entry and then broadcasts a message <VSTIG_PUT, vstig_id, key, value1, timestamp1, robot_id1>. This mechanism allows robots to automatically update information after temporary disconnections or when random message loss occurs.

Message queue optimizations. The fact that messages are sent only when an entry is written or read ensures that maximum resources are concentrated on 'hot' data. This allows the robots to avoid expensive updates of the entire tuple space. In this way, a virtual stigmergy structure can grow in size if necessary, knowing that minimal overhead is necessary to keep ‘hot’ data up-to-date. However, the fact that each access to a virtual stigmergy structure entails the production of a message can quickly fill the message queue. To avoid this problem, when a message is queued, the BVM checks for existing messages in the outbound queue that refer to the same entry in the same virtual stigmergy structure, and only keeps the most up-to-date message.

F. Integrating and Extending Buzz

As an extension language, Buzz provides the necessary mechanisms to add new commands and add data structures that export parts of an underlying system (e.g. ROS \[21\]).

Adding new data structures. Sensor readings are a common aspect that must be integrated with Buzz. Typically, this is realized by adding dedicated data structures (e.g., tables) to the BVM. For instance, the e-puck is equipped with 8 proximity
sensors placed in a ring around the robot body. The C code to create a Buzz table that contains these values is as follows:

```c
// The Buzz virtual machine, assumed already initialized */
buzzvm_t vm;
// The proximity readings, assumed already filled */
int prox[8];
// Create a new Buzz table for the proximity readings */
buzzvm_push_table(vm);
buzzobj_t pt = buzzvm_stack_at(vm, 1);
buzzvm_pop(vm);
// Store the proximity readings in the table */
for(int i = 0; i < 8; ++i) {
    buzzvm_push(pt);
    buzzvm_pushi(vm, i);
    buzzvm_pushi(vm, prox[i]);
    buzzvm_gstore(vm);
}
// Store the table as the global symbol "prox" */
buzzvm_push(vm, buzzvm_string_register(vm, "prox"));
buzzvm_pushi(vm, 8);
buzzvm_gstore(vm);
```

In Buzz, one could then write the following:

```buzz
if(prox[0] > 100 or prox[7] > 100) {
    # obstacle in front, turn around
}
```

Adding new commands. Adding new commands allows a programmer to extend Buzz with new capabilities. External C functions are integrated with Buzz as C closures. For instance, the code to integrate a function that sets the e-puck wheel speeds is as follows (error checking is omitted for brevity):

```c
int set_wheels(buzzvm_t vm) {
    /* Read arguments */
    buzzvm_lload(vm, 2);
    buzzvm_lload(vm, 1);
    int leftwheel = buzzvm_stack_at(vm, 2);
    int rightwheel = buzzvm_stack_at(vm, 1);
    /* Set wheel speed using low-level e-puck library */
    buzzvm_pushcc(vm, buzzvm_function_register(vm, set_wheels));
    /* Return no value to Buzz */
    return buzzvm_geto(vm);
}
```

As a result, in Buzz one could write:

```buzz
# Set e-puck wheel speeds
set_wheels{10.0, 5.0}
```

Calling Buzz functions from C. It is sometimes necessary to call a (native or C) closure from C code. This happens, for instance, when the execution loop is managed outside Buzz. In this case, a Buzz script is typically organized in functions such as `init()`, `step()`, and `destroy()`. These functions are called by the underlying system when necessary. As a simple example, let us take the increment function:

```c
/* Call the function with:*/
buzzvm_function_call();
/* Push the function argument on the stack */
buzzvm_pushi(vm, 5);
/* Call the function with:*/
* 1. The VM data
* 2. The function name
* 3. The number of parameters passed */
buzzvm_function_call(vm, "inc", 1);
```

V. EXAMPLES

The objective of this section is to showcase Buzz, by providing examples of common swarm algorithms for motion and task coordination. These examples show how to build complex swarm behaviors starting from simpler primitives, and demonstrate the generality and composability of Buzz. The examples are also designed to suggest how a library of reusable swarm behaviors could be constructed using Buzz. The scripts were tested with ARGoS [22], an accurate, physics-based simulator that includes models for Spirii, a commercial quad-rotor robot.

A. Motion and Spatial Coordination

In heterogeneous swarms, the presence of robots with diverse motion means can enhance the capabilities of the swarm [23]. Buzz does not offer native motion primitives, leaving the designer with the freedom to set ones that are most suitable for each robot. In this section, we assume that every robot is endowed with a primitive `goto()`, which takes a 2D direction as input in the form of a table `{x, y}`. The direction is then transformed into low-level actuation accordingly to the specific motion means of a robot (e.g., wheels, propellers).

Pattern formation [6] is a basic swarm behavior that has been employed in several applications including flocking [7] and area coverage [8]. One of the most common approaches, and the one we show here, is to implement pattern formation through virtual physics [6]. Essentially, every robot is considered as a charged particle immersed in a potential field, which is ‘virtual’ because it is calculated from neighbor positioning data. The direction vector of each robot is calculated as the weighted sum of the virtual forces that derive from the interaction of a robot with its neighbors. We employ the following formula [9] to calculate the magnitude of the virtual force $f_n$ due to a neighbor $n$:

$$|f_n| = \frac{\epsilon}{d_n^3} \left(\frac{\delta}{d_n} - \left(\frac{\delta}{d_n}\right)^2\right),$$

where $d_n$ is the current distance between the robot and its neighbor $n$, $\delta$ is the target distance, and $\epsilon$ is a gain. The direction vector a robot must follow is calculated as the average of the vectors of the virtual forces $f_n$:

$$f = \frac{1}{N} \sum_{n=1}^{N} f_n.$$

The neighbors structure provides a natural way to implement this behavior. First, one must implement the function that calculates $|f_n|$:

```c
/* Virtual force parameters (manually fitted)*/
DELTA = 50.
EPSILON = 2700.

/* Virtual force magnitude*/
function force_mag(dist, delta, epsilon) {
    return -(epsilon / dist) * ((delta / dist) - (delta / dist)^2);
}
```

[http://www.pleiades.ca](http://www.pleiades.ca)
Next, we need a function to calculate $f_n$ from the positional information of a neighbor. This function is then used in `neighbor.reduce()` to calculate $f$:

```javascript
# Virtual force accumulator
function force_sum(rid, data, accum) {
  var fm = force_mag(data.distance, DELTA, EPSILON)
  accum.x = accum.x + fm * math.cos(data.azimuth)
  accum.y = accum.y + fm * math.sin(data.azimuth)
  return accum
}
# Calculates the direction vector
function direction() {
  var dir = neighbors.reduce(force_sum, {x=0,y=0})
  dir.x = dir.x / neighbors.count()
  dir.y = dir.y / neighbors.count()
  return dir
}
# Executed at each step
# The loop is assumed managed outside Buzz
function step() {
  goto(direction())
}
```

An example usage of the barrier is presented in Sec. V-C.

### C. Separation into Multiple Swarms

Separation is a basic motion behavior whereby a group of robots divides into two or more subgroups. A possible way to implement this behavior in Buzz consists of defining two swarms, and use pattern formation to impose a short distance between kin robots, and a long one between non-kin ones. The following modifications to the pattern formation algorithm in Sec. V-A capture the interaction among the different swarms:

```javascript
# Virtual force parameters (manually fitted)
DELTA_KIN = 50.
EPSILON_KIN = 2700.
DELTA_NONKIN = 150.
EPSILON_NONKIN = 8000.
# Virtual force accumulator for kin robots
function force_sum_kin(rid, data, accum) { ... }
# Virtual force accumulator for non-kin robots
function force_sum_nonkin(rid, data, accum) { ... }
# Calculates the direction vector
function direction() {
  var dir
dir = neighbors.kin().reduce(force_sum_kin, {x=0,y=0})
dir = neighbors.nonkin().reduce(force_sum_nonkin, dir)
dir.x = dir.x / neighbors.count()
dir.y = dir.y / neighbors.count()
return dir
}
```

The decision on which group a robot belongs to depends on the application. In the following, we concentrate on the case in which two different targets are present in the environment. Each target is marked by a colored light—one red, one blue. The Spiri is equipped with a frontal camera that can detect
a target and its color. We assume that not all of the robots are capable of detecting the target, due to obstructions or sensor range limitations. The uninformed robots must rely on the information shared by the informed robots to pick the closest target. A possible solution to achieve this is employing virtual stigmergy, in which each robot advertises its distance to the closest target and its color:

```python
sred.select(mytargetdata.color == COLOR_RED)
sred = swarm.create(COLOR_RED)
```

Once the choice is done and the barrier is overcome, the robots form two swarms and move accordingly:

```python
NUM_ROBOTS = 10
MAX_DISTANCE = 10000 # 100 meters
TARGET_VSTIG = 2

# Create virtual stigmergy
targetvstig = stigmergy.create(TARGET_VSTIG)

# Get target data
var mytargetdata = {}
if(camera.targetdata)
    # Can see the target directly
    mytargetdata = camera.targetdata
targetvstig.put(id, mytargetdata)
targetfound = 1
else {
    # Can’t see the target directly
    mytargetdata.dist = MAX_DISTANCE
    mytargetdata.color = nil
    mytargetdata.closest = nil
    targetfound = nil
}
# Keep monitoring neighbors until everybody
# advertises a distance
while(not targetfound) {
    targetfound = 1
    mytargetdata = neighbors.reduce( function(rid, rdata, accum) {
        var d = targetvstig.get(rid)
        if(d == nil) {
            if(d.dist < DISTANCE_MAX) {
                if(accum.dist > d.distance + d.dist) {
                    accum.dist = rdata.distance + d.dist
                    accum.closest = rid
                    accum.color = d.color
                }
            }
        } else targetfound = nil
    }, mytargetdata)
    return accum
}
# Advertise choice
targetvstig.put(id, mytargetdata)
# Neighbors done?
if(targetfound) barrier_ready()
}
# Wait for others to finish
barrier_wait(NUM_ROBOTS);
# When we get here, everybody has picked a target
```

Experimental setup. Our experimental setup consists of a square arena of side $L$ in which $N$ robots are scattered. The coordinates $(x, y)$ of each robot are chosen uniformly from $U(-L/2, L/2)$. We define the robot density $D$ as the ratio between the area occupied by all the robots and the total area of the arena. To ensure comparable conditions across different choices of $N$, we keep the density constant ($D = 0.1$) and calculate $L$ with:

$$D = \frac{N\pi R^2}{L^2} \Rightarrow L = \sqrt{\frac{N\pi R^2}{D}},$$

where $R = 8.5 \text{ cm}$ is the radius of a marXbot. We focus our analysis on two parameters that directly affect the properties that we intend to analyze: (i) The number of robots $N$, which impacts scalability; and (ii) The message dropping probability $P$, which affects robustness and accounts for an important, unavoidable phenomenon that influences the efficiency of current devices for situated communication. For $N$, we chose $\{10, 100, 1000\}$; for $P$, we chose $\{0, 0.25, 0.5, 0.75, 0.95\}$. Each experimental configuration $\langle N, P \rangle$ was tested 100 times.

Virtual stigmergy. To analyze the efficiency of virtual stigmergy, we devised an experiment in which the robots must agree on the highest robot id across the swarm. This experiment is representative of a wide class of situations in which a robot swarm must agree on the maximum or minimum value of a quantity (e.g., sensor reading). As performance measure, we employed the number of time steps necessary to reach global consensus. We report in Fig. 3 the script we executed and the data distribution we obtained. Our results indicate that, up to $P = 0.75$, the number of time steps necessary to reach consensus is affected weakly by $N$, and practically unaffected by $P$. Interestingly, for $\langle N = 1000, P = 0.75 \rangle$, consensus is reached in at most 15 time steps (a time step corresponds to 0.1 s in our simulations). This positive result can be explained by noting that, with $P = 0.75$, 3 messages out of 4 are lost; however, the uniform distribution of the robots ensures that, on average, each robot has more than 3 neighbors. Thus, messages can still flow throughout the network. The effect of packet dropping is apparent for very pessimistic values ($P = 0.95$).

Neighbor queries. To analyze the performance of neighbor queries, we devised an experiment in which the robots must construct a distance gradient from a robot acting as source. This experiment is representative because the formation of gradients is a fundamental coordination mechanism in swarm behaviors. As performance measure, we employ the time necessary for every robot to estimate its distance to the source. The script and the data plot are reported in Fig. 4. The dynamics are analogous to virtual stigmergy: convergence time depends weakly on $N$ and is unaffected by $P$ up to $P = 0.75$; for $\langle N = 1000, P = 0.75 \rangle$ convergence is reached in a maximum of 13 time steps; for $P = 0.95$, convergence times increase sensibly. Again, this is arguably due to the dense distribution of robots, which facilitates the circulation of messages across the swarm, thus mitigating the effects of message dropping.

4When a coordinate choice causes physical overlap with already placed robots, a new coordinate is picked until no overlap occurs.
that is, a collection of connected computing devices scattered in a swarm of aerial robots unable to communicate directly. Dantu et al. designed for self-assembly applications was proposed in [28]. A programming methodology inspired by embryogenesis and have been proposed in the sensor network community [27].

Systems. Various abstractions and programming languages and tools have been proposed to support high-level, logic description of swarm robotics, SWARMORPH-script [26] is a bottom-up behavior-based scripting language designed to achieve morphogenesis with mobile robots. The last decade saw the introduction of the first top-down approaches to the development of distributed computing systems. Various abstractions and programming languages have been proposed in the sensor network community [27]. A programming methodology inspired by embryogenesis and designed for self-assembly applications was proposed in [28]. Dantu et al. proposed Karma [29], a framework that combines centralized and distributed elements to perform task allocation in a swarm of aerial robots unable to communicate directly.

Proto [30] is a language designed for “spatial computers,” that is, a collection of connected computing devices scattered in a physical space. The spatial computer is modeled as a continuous medium in which each point is assigned a tuple of values. The primitive operations of Proto act on this medium. The LISP-like syntax of Proto is modular by design and produces predictable programs. Proto shines in this medium. The LISP-like syntax of Proto is modular by design and produces predictable programs. Proto shines in scenarios in which homogeneous devices perform distributed spatial computation—the inspiration for Buzz’ neighbors construct was taken from Proto. However, as a language for robotics, Proto presents a number of limitations: (i) As a functional language, maintaining state over time is cumbersome; (ii) Every node handles only single tuples; (iii) Support for robot motion is limited; (iv) No explicit support for heterogeneous devices is present. Part of these issues have been addressed in [31].

Meld [32] is a declarative language that realizes the top-down approach by allowing the developer to specify a high-level, logic description of what the swarm as a whole should achieve. The low-level (communication/coordination) mechanisms that reify the high-level goals, i.e., the how, are left to the language implementation and are transparent to the developer. The main concepts of the language are facts and
rules. A fact encodes a piece of information that the system considers true at a given time. A computation in Meld consists of applying the specified rules progressively to produce all the true facts, until no further production is possible. Meld supports heterogeneous robot swarms by endowing each robot with facts that map to specific capabilities. A similar concept exists in Buzz, with robot-specific symbols (see Sec. [V-B]).

The main limitation of Meld for swarm robotics is the fact that its rule-based mechanics produce programs whose execution is difficult to predict and debug, and it is thus impossible to decompose complex programs into well-defined modules.

Voltron [33] is a language designed for distributed mobile sensing. Voltron allows the developer to specify the logic to be executed at several locations, without having to dictate how the robots must coordinate to achieve the objectives. Coordination is achieved automatically through the use of a shared tuple space, for which two implementations were tested—a centralized one, and a decentralized one based on the concept of virtual synchrony [34]. In Buzz, virtual stigmergy was loosely inspired by the capabilities of virtual synchrony, although the internals of the two systems differ substantially. Voltron excels in single-robot, single-task scenarios in which pure sensing is involved; however, fine-grained coordination of heterogeneous swarms is not possible, because Voltron’s abstraction hides the low-level details of the robots.

VIII. CONCLUSIONS AND FUTURE WORK

We presented Buzz, a novel programming language designed for large-scale, heterogeneous robot swarms. The contributions of our work include: (i) a mixed paradigm for the implementation of robot swarms, which allows the developer to specify fine-grained, bottom-up logic as well as reason in a top-down, swarm-oriented fashion; (ii) the definition of a compositional and predictable approach to swarm behavior development; (iii) the implementation of a general language capable of expressing the most common swarm behaviors.

Besides these contributions, we believe that one of the most important aspects of Buzz is its potential to become an enabler for future research on real-world, complex swarm robotics systems. Currently, no standardized platform exists that allows researchers to compare, share, and reuse swarm behaviors. Inescapably, development involves a certain amount of re-coding of recurring swarm behaviors, such as flocking, barriers, and creation of gradients. The design of Buzz is motivated and nurtured by the necessity to overcome this state of affairs. We hope that Buzz will have a lasting impact on the growth of the swarm robotics field.

Future work on Buzz will involve several activities. Firstly, we will integrate the run-time into multiple robotics platforms of different kinds, such as ground-based and aerial robots. Secondly, we will create a library of well-known swarm behaviors, which will be offered open-source to practitioners as part of the Buzz distribution. This will be the first true collection of ‘swarm patterns’, in the classical sense the word ‘pattern’ assumes in software engineering [35]. Finally, we will tackle the design of general approaches to swarm behavior debugging and fault detection. These topics have received little attention in the literature, and Buzz constitutes an ideal platform to study them. In particular, we will study more in depth the impact of the network topology on the efficiency of message passing, and we will investigate adaptive methods to detect and mitigate the issues of unoptimal topologies.

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