

BittyBuzz: A Swarm Robotics Runtime for Tiny Systems

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Abstract—Swarm robotics is an emerging field of research which is increasingly attracting attention thanks to the advances in robotics and its potential applications. However, despite the enthusiasm surrounding this area of research, software development for swarm robotics is still a tedious task. That fact is partly due to the lack of dedicated solutions, in particular for low-cost systems to be produced in large numbers and that can have important resource constraints. To address this issue, we introduce BittyBuzz, a novel runtime platform: it allows Buzz, a domain-specific language, to run on microcontrollers while maintaining dynamic memory management. BittyBuzz is designed to fit a flash memory as small as 32 kB (with usable space for scripts) and work with as little as 2 kB of RAM. In this work, we introduce the BittyBuzz implementation, its differences from the original Buzz virtual machine, and its advantages for swarm robotics systems. We show that BittyBuzz is successfully integrated with three robotic platforms with minimal memory footprint and conduct experiments to show computation performance of BittyBuzz. Results show that BittyBuzz can be effectively used to implement common swarm behaviors on microcontroller-based systems.

I. INTRODUCTION

Swarm robotics is a research area that studies coordination in groups of relatively simple robots, leveraging local interactions to generate emergent global behaviors. It is inspired by societies of insects, where groups can achieve tasks beyond the capabilities of the individuals [1]. With properties such as scalability, robustness, autonomy, decentralization [2], swarm robotics allow a wide variety of applications, including nanomedicine, space exploration, search and rescue missions, and generally tasks in dangerous areas [2]. Despite all these possible applications, most of the field of swarm robotics is still firmly at the research stage. For reasons related to cost, time, space and complexity, swarm applications require small and low-cost robots. Multiple robotic platforms meeting these specifications are widely used for research (e.g. the Kilobot [3]). Due to their low-cost, such systems come with a limited amount of computing resources and sometimes make swarm-oriented software solutions developed in simulation unusable. If programming cooperative behaviours for swarm robotics has always been a challenging task [4], doing it for resource-constrained swarm systems only makes it harder.

In fact, the development process for swarm robotics applications is sometimes a slow and tedious task requiring a

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lot of effort from the developer. The lack of dedicated tools focusing on swarm interactions is to blame for this situation: it forces developers to “reinvent the wheel” when trying to integrate well-known algorithms to new applications. To solve the problem, some previous work proposed domain specific languages (DSLs) to raise the level of abstraction and provide common programming primitives, easing the development task. For instance, Koord [5] is an event-driven language which uses shared variables for coordination in distributed robotics applications, with capabilities applicable to swarm robotics. Protelis [6] is also an example of a DSL used for aggregate programming. In the same spirit, the framework DRONA [7] proposes the P language for distributed mobile robots applications development. Pincioli et al. created Buzz [8], a DSL for heterogeneous robot swarms. Buzz gives a configurable level of abstraction (swarm or individual robot) to the developer depending on their needs. It also lays down some important primitives that are necessary for swarm-oriented programming.

Unfortunately, these DSLs do not tackle the resource limitation problem in their implementations and may therefore be unusable in many practical applications. In fact, even the Buzz virtual machine, which in theory only takes 12 kB of memory, can quickly fill the flash when combined with the native firmware of certain robots. Furthermore, the RAM consumption during application execution can easily exceed the one available on some robots (as little as 2 kB for the Kilobot). Faced with such an issue, we propose a system offering the same capabilities as Buzz for swarm systems composed of resource-constrained robots.

In particular, this system should offer, to name a few: swarm-level abstractions, heterogeneous robot support, communication neighbor operations. The system should also be modular, allowing the user to reduce resource consumption by selecting the features to use depending on the implemented behavior. It should be able to fit systems like the Kilobot with 32 kB of flash and 2 kB of RAM, and other resource-constrained robotic and swarm research platforms.

Answering these needs, this article introduces BittyBuzz, an implementation of the Buzz Virtual Machine for microcontrollers. This implementation roughly uses the same structure as Buzz and supports 100% of its code, with very few limitations when compared to Buzz, to address resource constraints. The main contributions of this paper are:

- the development of a swarm-oriented runtime environment capable of defining the behavior of heterogeneous swarms of robots with as small as 32 kB of flash and 2 kB of RAM;
- the adaptation and optimization of Buzz’s capabilities

- (generality, mixed bottom-up/top-down logic, etc.) to resource-constrained platforms;
- the integration of BittyBuzz with three different robot hardware platforms used for research in swarm robotics.

BittyBuzz is released as open-source software and can be downloaded from our repository¹. We evaluated BittyBuzz’s performance on the Bitcraze Crazyflie, the K-Team kilobot, and the Zoid robotic platforms. All these platforms are currently used in research on swarm robotics.

The rest of this paper is organized as follows. In Section 2, we discuss some of the work related to BittyBuzz, while explaining the differences. Section 3 presents BittyBuzz’s features and design principles while comparing them to Buzz’s. Section 4 explains the design choices that were made to overcome the resource constraints. Section 5 presents an overview of the BittyBuzz-integrated robotic platforms. In Section 6 we evaluate the VM performance. We then draw the concluding remarks in Section 7.

II. RELATED WORK

A variety of previous works discussed the development of dedicated tools for swarm systems, as well as the creation of optimized frameworks for resource-constrained devices (see Table I for a summary). Micropython [9] is a lightweight and efficient implementation of the Python 3 programming language. That implementation is optimized to run on microcontrollers and in constrained environments. It is composed of a full Python runtime and a subset of the Python standard library while able to fit a 256 KB code space and run with 16 kB RAM. Micropython has been proven to be a good option for rapid development of IoT devices with tested and verified libraries [10]. Currently, its main use targets are: device development and testing, sensor design, monitoring and configuration tools in design of complex applications, and education purposes [10]. For instance, [11] presents a prototype of an educational mobile robot based on MicroPython. Even by addressing the resource constraint issue, this language uses more memory than BittyBuzz and does not offer any swarm primitives or neighbor management that make BittyBuzz tailored for swarm application development.

Artoo [12] is another development tool for microcontrollers and a micro-framework designed for robotics. The framework provides a powerful DSL for robot control and physical computing. It works on Ruby and borrows some concepts and code from Sinatra [13]. Supporting 15 different platforms, among which the Bitcraze Crazyflie (one of our targets with BittyBuzz), Artoo allows developers to create solutions that incorporate multiple, different hardware devices at the same time. However, Artoo is not designed for decentralized swarm application design: it requires the user to connect one or multiple robots to a centralized control computer, which is not suitable for inherently distributed swarm systems.

The Zephyr project [14] is also worth mentioning as it unites developers and users in building a small, scalable

real-time operating system (RTOS) optimized for resource-constrained devices on multiple architectures. The goal of the project is to create an open, collaborative environment to deliver a RTOS that will answer the changing demand of the connected devices. The system supports multiple boards and is easily portable across platforms. It has a different approach to the resource constraint problem when compared to BittyBuzz, simply offering a configurable RTOS that can be adapted depending on the user’s needs.

Other existing works focus on the development of frameworks and/or DSLs for swarm applications. For instance, Koord [5] is a swarm-oriented language developed to make platform-independent code portable and verifiable. Koord proposes various useful features for coordination in a swarm, such as shared variables between the robots and state recording. However, Koord does not focus on resource constraints, which is the main contribution of this paper.

Another example is DRONA [7], a framework for building reliable distributed mobile robotics (DMR) applications. DRONA provides a state-machine based language (P) for event-driven programming. P is a high-level language that, once compiled, generates C code that can be directly deployed in ROS. Protelis [6] is another language developed to provide a practical and universal platform for aggregate programming. Aggregate programming, unlike the traditional device-centric programming, is concerned with the behavior of a collection of devices - that can be assimilated to a swarm of robots. The language is hosted in and integrated with Java. Yi et al. [4] propose an actor-based programming framework for swarm robotic systems: they present a bottom-up programming approach based on a new control unit, the “actor”. An actor is the virtualization of the capabilities of a given robot, and it allows developers to design cooperative tasks without dealing with the intricacies of robotic algorithms and specific robot brands. Similarly to Koord, these frameworks are not suitable to run on resource-constrained devices.

Peng et al. [15] present EmSBoT, a component-based framework targeting resource-constrained devices (using 13 kB of flash memory and 5 kB of RAM). It is built upon μ COS-III with real-time support. Even though it is network-focused, this framework supports the development of swarm robotics applications, albeit without the swarm-oriented features of BittyBuzz. OpenSwarm [16] is an OS designed for severely computationally constrained robots (using 1 kB RAM and 12 kB of flash). It enables the developer to design platform-independent solutions, that can easily be applied to swarm robotics, as showed in their experiments. Both EmSBoT and OpenSwarm only provide low-level programming and work on a small subset of platforms, while Buzz and BittyBuzz are based on a virtual machine (VM), meaning that the Buzz code is device-independent and can run on any system where the virtual machine is running without need of recompilation.

Overall, although some of those frameworks are lightweight, they either do not focus on resource-constrained systems or do not meet the key requirements of a successful programming language for swarm robotics (decentral-

¹<https://github.com/buzz-lang/BittyBuzz>

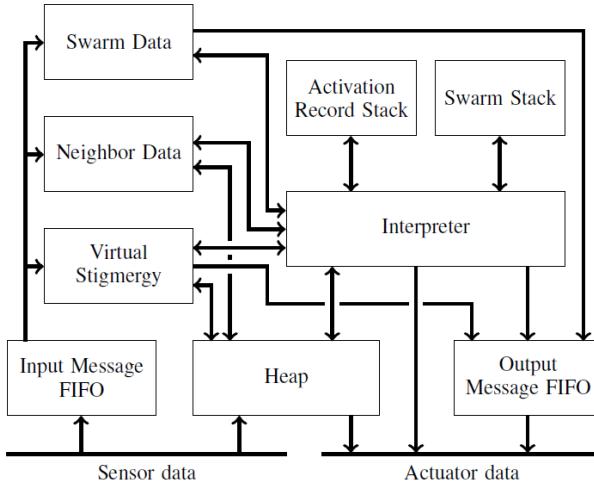


Fig. 1. BittyBuzz virtual machine structure [8]

ized control, spatial computing, neighbor communication, etc. [8]). Buzz [8] is a swarm-specific language that was developed to address the lack of software development tools in swarm robotics. Buzz offers a multitude of interesting features for swarm application development, including but not limited to: heterogeneous support, swarm-level abstractions, neighbor operations and a consensus system (the “virtual stigmergy”). The work presented in this paper is an adaptation of Buzz optimized to fit resource-constrained systems, such as microcontrollers. BittyBuzz supports the entirety of the Buzz language, with a runtime that can be adapted to different memory and computation constraints. We extended the support of BittyBuzz to three hardware platforms (Bitcraze Crazyflie [17], Kilobot [18], and Zoids [19]) which are targeted towards resource-constrained robot swarms, but without a common framework or language. BittyBuzz provides a common language that allows the user to develop behaviors with minimal knowledge of the specifics of the hardware.

III. BITTYBUZZ STRUCTURE

BittyBuzz virtual machine. BittyBuzz, just like Buzz, has a run-time platform based on a custom virtual machine written in C. The BittyBuzz virtual machine (BBZVM) structure and operation is the same as Buzz: the virtual machine operates in discrete time steps, each of which consists in a sequence of sub-steps: 1) the BBZVM collects the robot’s sensor readings, which would typically be stored in memory; 2) the BBZVM collects incoming messages and updates relevant data structures related to communications (e.g. the *neighbors* data structure); 3) the BittyBuzz interpreter is called to execute a Buzz script; 4) and finally the BBZVM outputs actuator signals and outgoing messages. The BBZVM has a variable size, and can be as small as 17.1 kB (see Section III-A for details). Its structure is presented in Figure 1.

Swarm-level abstraction. A team of robots is considered as a swarm. Buzz allows the developer to handle robot swarms as a first-class language object through the *swarm*

primitive type. This capability is preserved in BittyBuzz. That way, swarms can be easily created and robots can join or leave a swarm, optionally based on a specific condition.

New swarms can also be created as a result of an intersection, union or difference between existing swarms. All the robots in a swarm can then be assigned a shared task [8].

Heterogeneous robots support. Buzz is an extension language and was explicitly designed to support heterogeneous robot swarms. Hence, it natively only handles the logic parts of the robotic system (common to all robotic systems). That allows the developer to extend Buzz by adding new robot-specific commands (see Section III-B for BittyBuzz extensions) [8].

Situated communication. All the robots running Buzz are assumed to have a device capable of broadcasting and receiving messages within a limited range provided direct, unobstructed line-of-sight to and from neighbors. That mechanism gives each robot the ability to inform its neighbors of its position and makes each robot aware of its neighbors’ positions. When a device receives a message, it detects the relative distance and angle of the sender, making it easier to use the information in a swarm application (for instance for obstacle avoidance). Situated communication is frequently used for different algorithms in swarm robotics [8].

Virtual Stigmergy. Buzz implements the Virtual Stigmergy (VS), a conflict-free replicated data structure that is used to provide consensus on a set of key-value pairs across the entire swarm [20]. The VS is essentially seen by the programmer as a shared table: each *put* operation by a member of the swarm triggers an automatic update in the others, with mechanisms to avoid conflicts. The VS is available in BittyBuzz with its complete features, and it is completely transparent to the user as a key-value data store through the *put* and *get* methods.

Neighbor operations. Buzz and BittyBuzz provide a *neighbors* data structure that allows data collection and processing from neighboring robots. This type of neighbor operation is the foundation of spatial computing [21] and widely used in swarm robotics. The *neighbors* structure is a dictionary indexed by robot id containing the robot distance as well as the azimuth and elevation angles of each neighboring robot, as detected by the BBZVM, and updated at each step through *situated communication*. It supports three spatial operations: iteration, transformation and reduction, with functions such as *map()*, *foreach()*, *reduce()* and *filter()*. The only difference with Buzz is that the functions *kin()* and *nonkin()* that allow the programmer to filter neighbors based on swarm membership are not implemented in BittyBuzz to reduce its memory footprint.

The *neighbors* data structure also allows direct communication with the robots in the neighborhood, by the means of a *broadcast* operation. The neighbors that want to receive messages on a given topic can subscribe to it with the *listen* function. A robot can then also ignore the messages related to a subscribed topic by using the *ignore* function.

Thanks to these features, BittyBuzz lets developers work at different levels of abstraction according to their needs,

TABLE I
COMPARISON OF EXISTING FRAMEWORKS FOR ROBOTS APPLICATIONS DEVELOPMENT.

System/Framework	Swarm support	Heterogeneous	DSL	Embedded	Support for resource constraints
MicroPython [9]		N/A	N/A	✓	✓
Artoo [12]		N/A	N/A		✓
Zephyr project [14]		N/A	N/A	✓	✓
DRONA [7]	✓		P	✓	
Protelis [6]	✓	✓	Protelis	✓	
Koord [5]	✓	✓	Koord	✓	
Actor-based framework [4]	✓	✓	(unnamed)	✓	
Emsbot [15]	✓	✓	N/A	✓	✓
OpenSwarm [16]	✓	✓	N/A	✓	✓
Buzz [8]	✓	✓	Buzz	✓	
BittyBuzz	✓	✓	Buzz	✓	✓

develop intuitive code for heterogeneous swarms and easily access neighborhood information. Thus, one can focus on the swarm behavior as a whole with a top-down approach or use the robot-wise operations in a bottom-up fashion. Those are all essential features for a swarm-oriented programming language, and are all implemented in BittyBuzz.

A. BittyBuzz virtual machine configuration

Reducing the BBZVM's size to fit smaller microcontrollers needed some adaptations to the original Buzz virtual machine. Besides the two unimplemented functions mentioned above, we provide some parameters to modulate the BBZVM's size and memory consumption depending on the application. The configurable attributes range from heap and stack size definition to optional feature (de)activation.

The swarm structure as well as its operations can be disabled if needed. In this case, the swarm level abstraction will no longer be exploitable, and all the instructions will be robot-wise. The neighbor operations can also be disabled by the user, removing the situated communication. Similarly, the virtual stigmergy structure can be deactivated.

BittyBuzz also has a memory usage reduction mode that allows the developer to drastically reduce RAM consumption at the expense of the flash.

All these configurations are selected at compilation time by the user, depending on the hardware and application.

B. BittyBuzz extension

The ability to extend BittyBuzz (and Buzz) is a particularly useful feature when using the language for a new robotic platform. For instance, the *goto()* function's implementation and number of parameters is highly platform dependent and can be redefined for all the new robots by using external C closures. Defining such closures in BittyBuzz can be done in a very similar way to Buzz. In BittyBuzz, to use a new function in the Buzz script is as simple as writing a C function. The created function can then be registered in the BBZVM with a single call to *bbzvm.function_register(fnameid, funp)*.

IV. BITTYBUZZ: OVERCOMING RESOURCE CONSTRAINTS

Different strategies were used to make BittyBuzz efficient in terms of resource consumption. This section will

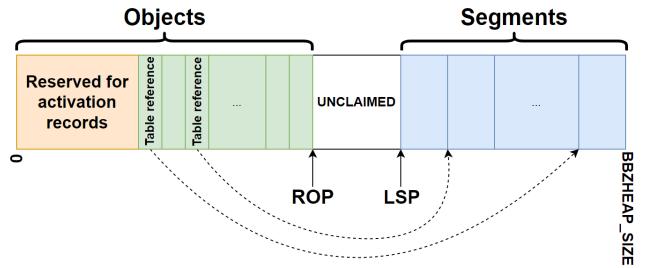


Fig. 2. Illustration of BittyBuzz's heap: the object section containing the activation records section and the allocated objects (non-structured types and table references) in light green, the unclaimed section in white, the segment section in light blue, and the two pointers ROP and LSP.

present the dynamic memory management mechanisms implemented, as well as other important optimization points.

A. Dynamic memory management

1) *Pre-allocated heap*: BittyBuzz has a pre-allocated heap whose size is specified by the developer. The heap is represented by a static buffer with three sections: the object section (also containing the activation records of closure calls), the segment section and the unclaimed section. Two pointers are used to access the heap: the rightmost object pointer (ROP) and the leftmost table segment pointer (LSP) as shown in Figure 2. Each object has two bytes containing the payload information and an additional metadata byte.

Regarding the storage in the heap, non-structured types such as nil, int, float and string are written from left to right with ROP always pointing to the last added object. For structured types (tables), an object is stored in the objects' section, referring to a data segment stored from right to left in the segments section. Each data segment has a user-defined number of key-value pairs and two metadata bytes containing information about the segment validity and a pointer to the next segment, if any. To save space in the case of arrays, the key-value pairs are seamlessly replaced by the values in the case where the keys are integers, in a way that resembles the table management in Lua [22].

2) *Garbage collector*: BittyBuzz has a simple and effective garbage collector algorithm which is frequently called

during the script execution, specifically before the execution of instructions. Each BittyBuzz heap entry has an attribute containing metadata, including some garbage collector bits. The algorithm starts by unmarking all the segments and objects. Then, it marks back the permanent objects that should never be garbage-collected, and the valid variables on the BittyBuzz stack. Finally, all the remaining unmarked objects are invalidated, and the heap pointers are re-positioned.

B. Optimizations and limitations

1) *Ring-buffers*: To reduce the time complexity for message queue management, BittyBuzz implements its own ring buffer. Ring buffers are used in several algorithms and are desirable in data stream use cases. They are buffers that are implemented to seamlessly loop on themselves, allowing constant time *push* and *pop* operations for queues. Previous works such as [23] propose a new implementation for multi-thread modifications of the ring buffer: we use a similar but simpler implementation running in a single thread. Each buffer is stored as an element size, a buffer capacity, a start index and an end index. With this information, insert, pop, and index access are done in constant time. We use ring buffers in BittyBuzz to store message queues, the communication payload buffer, and the *neighbors* data structure.

2) *Translated bytecode*: The available flash memory is also an important factor in the resource consumption management. To reduce the storage space, the original Buzz object (.bo file) is converted into a smaller BittyBuzz object (.bbo file). The optimizations mainly include the conversion from Buzz integers on 32 bits to BittyBuzz integers, which are on 16 bits. Floats are also converted to *bbzfloat* that only use 16 bits. All the non-instruction related strings are also stripped from the new object file to minimize file size.

3) *Optimized loops*: As discussed earlier, BittyBuzz uses a ring buffer to store neighbors' information. In fact, instead of using table segments on the heap, the implementation uses a static table of user-defined size for the neighbors' data. We optimize the looping through this data structure with a *foreach* operation: for each neighbor in the ring buffer, a data table is created to execute the needed instructions and then garbage-collected at the end of the iteration. The loop therefore uses constant instead of linear space on the heap.

4) *Swarm lists*: In BittyBuzz, a robot can be a member of a maximum of 8 swarms, numbered from 0 to 7. To keep track of which swarms a robot is a member of, we use a swarm list that is simply an 8-bit variable where the i-th bit represents whether a robot is a member of the i-th swarm (for example, if the bit 0 is 1 that means the robot is a member of the swarm 0). This list allows one to easily determine all the swarms of a given robot. When a robot is added to a swarm, BittyBuzz foresees to add the robot's swarm list to the outgoing message queue so that its neighbors can have the information and add it to their swarm table.

5) *Virtual stigmergy*: BittyBuzz, just like Buzz, has a virtual stigmergy system, although BittyBuzz's has some limitations with respect to the original version. For instance, BittyBuzz only has a unique instance of the stigmergy,

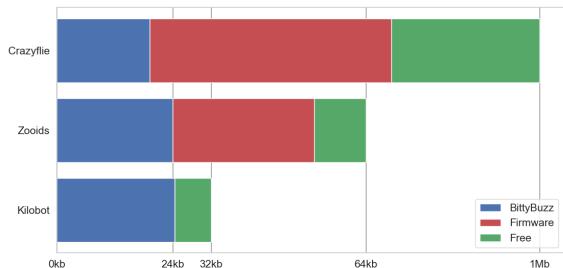


Fig. 3. Sizes of the BBZVM, the robot native firmware, and the available space for user bytecode for the three integrated robotic platforms: Bitcraze Crazyflie, K-Team Kilobot and Zoids

whereas one could create an arbitrary number of stigmergies in Buzz. In addition, the current implementation only takes strings as topics (keys) for the stigmergy.

6) *String manager*: Strings are a data type used in many programming languages to represent a sequence of characters. In BittyBuzz, in addition to variables used in the Buzz script, strings are used to identify global symbols and function names. In conventional implementations of strings, the data type is represented as an array of bytes (or words) [24]. However, such an implementation is memory consuming and needs an optimization to be effectively used in a resource constrained system. BittyBuzz represents strings as integers, by assigning a unique ID to each of the strings used in a given script, while the string content is placed in the flash RAM. This implementation reduces the memory footprint for strings as they always occupy 2 bytes instead of an array of unknown bytes. Some string IDs are necessary for BittyBuzz to operate correctly, and they are natively declared in the VM (for example the *stigmergy* keyword). As needed, the developer can create new string IDs for user-defined closures, using the macro *BBZSTRING_ID* (see III-B).

7) *Neighbors communication*: As mentioned earlier, BittyBuzz provides a publish-subscribe like mechanism, to allow robots to communicate. To send a message, a program calls the function *neighbors.broadcast(topic, value)*. Because of the extremely limited payload size of the targeted robotic platforms, BittyBuzz does not support sending tables as value. Also, since strings in BittyBuzz are represented by unique IDs (see IV-B.6) created during the execution, the code on the robots must be the same if the developer is trying to implement a communication-based behaviour. Specifically, the order and the number of strings literals must be the same. This final constraint is not limiting, as using the same script for all robots is the standard way Buzz scripts are operating.

V. ROBOTIC PLATFORMS

Figure 3 presents the flash memory usage of the BittyBuzz virtual machine and full-feature framework on the three following robotic platforms used in different swarm robotic projects. In all instances the memory footprint is under 24 kB with some variability between platforms based on available compiler optimizations (eg. floating point hardware support).



Fig. 4. Robotic platforms integrated with BittyBuzz. From left to right: Bitcraze Crazyflie, K-Team Kilobot, and Zooids

The **Kilobot** is an open-source low-cost small robot (33 mm diameter and 34 mm height) designed to ease the testing of algorithms for a large swarm (hundreds or thousands of robots), which can normally be time- and money-consuming. Each Kilobot can be made with US\$14 worth of parts and can be assembled in a relatively short time [18]. Kilobots provide a programmable controller, basic locomotion and local communication [25]. They use an ATmega 328p processor (8 bit@8MHz), a 32 kB flash, 2 kB SRAM, 1 kB EEPROM with a rechargeable battery, and they can be programmed in C [26].

The **Bitcraze Crazyflie** [27] is an open-source experimental flying development platform used for research and education in robotics. This relatively low-cost, easily expandable and upgradeable quadrotor is 92x92x29mm and weighs 27g. It can easily be assembled without any soldering and supports several expansion decks. Crazyflies are equipped with a STM32F405 MCU Cortex-M4 @ 168MHz, a 192 kB SRAM and a 1 MB flash for the main application. Finally, they have an 8 kB EEPROM [28].

Zooids [19] are small open-source and open-hardware robots, designed for a new class of human-computer interfaces for tabletop swarm interfaces. They each weigh 12 g for 26 mm in diameter and 21 mm in height. They contain a 48 MHz ARM microcontroller (STM32F051C8) equipped with a 64 kB flash memory and 8 kB SRAM.

VI. PERFORMANCE

We measured the overhead of the BittyBuzz runtime platform running on the most modest hardware platform we had targeted – the Zooids – to derive maximum utilization constraints and compare performance metrics with the original Buzz virtual machine implementation. We consider the total time taken for underlying virtual machine operations, message sharing etc. (*overhead*), which gives us the allocated slot for user-defined behavior; and maximum execution speed (in VM instructions per second) to determine the amount of work that can be done in that time frame. We use a 10Hz update frequency for reference.

Buzz measurements were performed on the Khepera IV [29], a wheeled robot running a complete operating system on top of a 800 MHz Cortex-A8 processor. Comparing BittyBuzz with this more complex platform lets us assess the further benefits of using the Buzz programming language for swarm software development on embedded systems.

Table II displays the differences in VM overhead for the two hardware platforms. We experience a slightly higher

delay on the Khepera despite the faster CPU due to interaction with the operating system eg. network and input/output buffering. Furthermore, Table III details the Buzz virtual machine instruction budget for 100 ms of execution in a timestep, thus targeting a 10 Hz timestep frequency. The upper bound on the constrained Zooid hardware occupies 459 instructions (ie. at most 918 bytes) amounting to 13% of the remaining space (see Figure 3). The instruction budget represents the amount of code that can be executed in a timestep, thus the remaining 87% can be used to store additional behaviors to switch to and from during execution.

TABLE II
VIRTUAL MACHINE OVERHEAD

VM Implementation	Hardware Platform	VM Overhead
Buzz [8]	Khepera IV	4.92 ms
BittyBuzz	Zooids	4.45 ms

TABLE III
MAXIMUM BUZZ INSTRUCTIONS FOR A TEN HZ Timestep

VM Implementation	Hardware Platform	Max instructions
Buzz [8]	Khepera IV	156 000
BittyBuzz	Zooids	459

Moreover, we carried out significant experiments and swarm tasks with Zooids in the context of hierarchical swarms [30], where a group of guide robots herd a lighter worker swarm and have it move across the environment, thus demonstrating the capabilities of our embedded framework.

VII. CONCLUSION

We presented BittyBuzz, a novel virtual machine for the Buzz language designed for resource-constrained microcontrollers. The contributions of this work include: 1) the development of a virtual machine for a dynamically typed language with dynamic memory management with as little as 32 kB of flash and 2 kB of RAM; 2) the full inclusion of Buzz's programming model (including neighbor queries, consensus, etc.) to a resource-constrained platform; 3) the integration of BittyBuzz with three different robotic platforms used for research in swarm robotics. In addition to these contributions, we believe that resource-constrained robotic platforms have an important part to play in the future of the internet of everything. A domain-specific dynamic language such as BittyBuzz will ease the development and prototyping of swarm applications. Our experiments show that BittyBuzz can be used for established swarm behaviors and that the communication model used by the virtual machine has sufficient performance even on severely constrained devices, enabling user behaviors to perform smoothly without noticeable delays. We show behaviors like exploration, bidding, and consensus building on various robotic platforms in the multimedia attachment, as well as a complex particle swarm experiment [30].

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