

CAREER: Verifiable Execution and Simulation of Cyber-Physical Systems

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Overview

Modern cyber-physical systems such as cars and aircraft are responsible for expensive equipment and human lives. To ensure that they operate in a safe manner, it is therefore important to *formally verify* the underlying code. However today, tools for execution, simulation and verification of cyber-physical systems are largely disconnected, and formal verification often ends up verifying a model of the code rather than the code that is actually executed, creating a gap in the verification. The proposed research will combine techniques for execution, simulation and verification in one programming language, bridging this gap and offering a methodology for end-to-end verification of cyber-physical systems.

Intellectual Merit

We broadly identify three families of work: synchronous languages such as Lustre, Esterel and Signal focus on software that is high-level and *executable*; Simulink, Modelica, Zelus, Ptolemy and others focus on *simulation*; Differential Dynamic Logic and SpaceEx, as well as many other model-checking-based approaches, focus on *verification*. However having different tools and languages poses an issue: in practice, translating from the verified version of critical software in one tool to its executable or simulated version in another tool often requires a manual rewrite of the verified implementation – opening the door to human errors. My vision is to *unify those approaches* to enable an *end-to-end verification* of cyber-physical systems without any manual translation. We propose the development of MARVeLus, a **new high-level programming language for the verification, execution and simulation of hybrid systems**. MARVeLus will be a *synchronous* language with *differential equations* and *dependent types*, and its verifier will generate verification conditions to be checked by external solvers. The language will compile down to the synchronous language Lustre, and this compiler will be formally verified, ensuring the absence of bugs in the compiler. This language will enable end-to-end verification of cyber-physical systems, be compatible with the SCADE industry standard, and compile to executable code in a formally verified way.

Broader Impacts

Using the new MARVeLus will educate and empower tomorrow's engineers to design cyber-physical systems with strong, formally verified guarantees. It will allow them to bridge gaps in the verification, and in particular to ensure that the code that is executed is also the code that was verified. In the long-run, our goal is to democratize the use of formal verification in the design of cyber-physical systems. The PI maintains strong ties with industry, including with Toyota, Collins Aerospace, and NASA. These connections will allow him to evaluate the new language on relevant projects provided by industry. The PI is planning to collaborate with a Detroit-area Title 1 middle school to enhance their curriculum and make the students more aware of safety issues and the availability of techniques to mitigate those issues, such as verification. The PI has also created a new class “AERO 350: Fundamentals of Aerospace Computing”, to give undergraduates a firm understanding of the use of computing in aerospace engineering. The class is now mandatory for all undergraduates in aerospace engineering. The PI has also added a verification module to the graduate class “AERO 552: Aerospace Information Systems”. Finally, the PI is active in the organization of workshops, having organized the 2020 and 2021 editions of the Verification Mentoring Workshop (VMW), and currently organizing the 2022 Programming Languages Summit (MWPLS).

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Proposal

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1 Motivation and Overview

The presence of software is steadily growing in our everyday life, and computer programs are playing increasingly important roles in many aspects of our existence. In many cases, such as in the case of software running in trains, car, aircraft and spacecraft, but also in chemical plants or on thermostats, the software interacts directly with its physical environment, thus forming a *cyber-physical system* (CPS). Many cyber-physical systems, especially control software in transportation, hold responsibility for expensive equipment or human lives, and malfunctions could lead to catastrophic outcomes, including deaths of users or operators. Moreover, because of their physical nature, CPSs are often impossible to test extensively, especially with respect to rare corner cases. As a result, testing is not sufficient to attain reasonable levels of trust.

To achieve a high level of confidence in the design of CPSs, many researchers have advocated for the use of *formal verification*, which uses mathematical techniques to ensure safety (or liveness) with a very high level of confidence. However, the state of the art shows a divide between languages and tools that are used for executing CPSs, simulating CPSs, and verifying CPSs. In particular, many tools support execution and simulation with no or very limited support for formal verification; and many tools designed for verification will not enable direct modular design and execution of the verified code. As a result, many verification efforts are made on a *model* of the software (the cyber part of the CPS) rather than on the source code – or the binary code – that actually runs on the CPS. Verifying a model creates a trust gap where the engineer or researcher has to trust that the model of the code is faithful to the running code, which may not be true because of errors in creating the model, or even simply because of bugs in the compiler.

The current state of the art can broadly be classified in three categories: synchronous languages, such as Lustre, SCADE, Esterel and Signal, are languages that are high-level and *executable*; Ptolemy, Simulink, Modelica, Zélos and others focus on *simulation*; Differential Dynamic Logic and SpaceEx, as well as many model-checking-based approaches, focus on *verification*. This CAREER project will design a new programming language called MARVeLus (Method for Automated Refinement Verification of Lustre) that will combine the three approaches to provide a **unified approach to executing, simulating and verifying cyber-physical systems. Combining all three approaches will, for the first time, enable end-to-end verification of cyber-physical systems, where the only trusted components are the verifier and the model of the physical environment.**

We will model CPSs as *hybrid systems*, systems with both discrete and continuous behaviors: in a hybrid system, software typically affects the system in *discrete* ways – variable assignment, actuator update – while the environment is most often governed by *continuous* laws of physics. At a high-level, MARVeLus will be a *synchronous* language with *differential equations* and *refinement types*: a synchronous approach inherits from decades of rigorous research on synchronous languages, and enables some compatibility with the SCADE suite, widely used to program CPSs; differential equations are needed to model the environment; and refinement types provide all the tools necessary to specify and verify CPSs.

Why is now the right time to do this work? Techniques for formal verification have made great progress over the last few years, and the field is maturing, especially in select application areas such as compilation or distributed systems [86, 81, 25]. For software not interacting with physics, there are now several tools performing verification of executable code [120, 121, 114, 127], many of which use refinement types or dependent types. Automation has also improved dramatically, with verification of projects requiring less and less manual interaction, e.g., in the field of distributed systems. On the other hand, synchronous languages have existed for over 40 years and are now widely used in industry – Scade [36] based on Lustre [56], but also Esterel [29] and Signal [84], and verification techniques based on model-checking were developed early on [57]. However, this only accounts for the purely discrete case. The integration with continuous dynamics and differential equations [28] has been made quite recently at the language level – including use in industry in

a new version of Scade [36] – but without verification capabilities for the continuous part. Finally, verification of hybrid systems has also made much progress in recent years, in particular with the use of zonotopes [6] and the automatic generation of invariants for continuous dynamics [53]. On all those fronts – formal verification in general and of hybrid systems in particular, integration of continuous dynamics with synchronous languages – many recent advances have been made. We believe the time is right to bring the verification of hybrid systems to the language level, to ensure the accurate verification of executable code.

Why build MARVeLus on a synchronous language? Synchronous languages such as Lustre, but also Esterel and Signal, were developed specifically to program embedded systems and cyber-physical systems in a safe way. For example, the Lustre language guarantees that any program will execute in bounded memory (with a known bound), and that its execution time will be predictable. The code generation is efficient, the result of decades of optimization development that we can leverage. Last but not least, Lustre is the basis of the SCADE tool, which is widely used in the aerospace and automobile industry, making it much more likely that MARVeLus will be used in industry on SCADE code.

Another tool widely used in some industries is Matlab/Simulink. However, Simulink is closed-source and does not have a widely accepted formal semantics, although there exist some academic attempts [24, 27]. This makes it very difficult to develop sound proof techniques, since soundness needs to be proved with respect to a semantics. On the other hand, SCADE and Simulink are very close in spirit, and we expect many of our results to be applicable to the Simulink ecosystem in the long run (but, likely, without soundness claims).

Why use refinement types? Refinement types have matured and shown much success recently, for example in the Liquid Haskell [127] and F^{*} [121] languages (note that F^{*} uses richer dependent types); both languages use off-the-shelf SMT solvers in their backend. It is time to explore their use for the verification of cyber-physical systems. One advantage of refinement types is that they allow the programmer to annotate the executable code directly, rather than specify properties externally. Moreover, in case a property cannot be proved fully automatically, refinement types allow the programmer to add some refinement annotations to help the solver.

Applications. To ensure its usability and adoption, the development of MARVeLus will be evaluated on some *case studies* and *collaborations with industry*. Our research agenda will include two case studies. The first case study will be on the Next-Generation Airborne Collision Avoidance System ACAS X, an industrial aircraft collision avoidance system currently under development by the Federal Aviation Administration. I have accomplished formal verification on ACAS X in the past, and am therefore very familiar with its design and specificities. The second case study will be the end-to-end verification of braking and swerving maneuvers for automobiles, for which I already collaborate with the Toyota Research Institute. This second case study is part of a broader vision of Toyota to equip their car with some formally verified modules ensuring the safety of the car at every instant. This application will likely lead to interesting technology transfer with Toyota, as well as their possible adoption of MARVeLus internally. The two case studies are chosen because they are industrial cases where reliability is extremely important. In some cases, similar case studies have already been achieved with other tools; but they usually only focus on verification, simulation *or* execution, whereas we will tackle all three aspects jointly. Applications and case studies are very important as they allow us to evaluate MARVeLus by identifying its strengths and weaknesses, thereby guiding its further development. During the development of MARVeLus, we hope to encounter new interesting case studies to further our experience with the language.

Outcomes and Impact. The research program outlined in this proposal will enable end-to-end formal verification of safety-critical applications such as aircraft collision systems. While current approaches to verification of cyber-physical systems typically verify a model of the software or the code at a high-level, we propose an approach that will lead to full verification of the cyber-physical system down to the binary code, leaving only two pieces to be trusted: the theorem prover and verifier performing the verification, and the dynamics of the environment. All other parts of the cyber-physical system will be mechanically verified, enabling the utmost level of trust and verification of safety-critical systems.

At a time where safety-critical, often autonomous, cyber-physical systems are responsible for expensive equipment and human lives, the systems' designers need powerful tools and methodologies to be able to guarantee that their creation is safe. This research program will design such tools, thereby empowering tomorrow's engineers to design cyber-physical systems with strong, end-to-end, formally verified guarantees.

Research plan. The specific research objectives are summarized below. More details can be found in Section 5.

1. **Design MARVeLus, a synchronous programming language with differential equations and refinement types.** Starting from the existing designs of the synchronous language Lustre [56], with differential equation in the style of Zélus [28], we will design a refinement type system in the style of F* [120], enabling the verification of safety and liveness properties. We will also draw inspiration from the languages Ptolemy [109], Dafny [85], Agda [30] and Coq [19], among others. We will design this language in a rigorous way and equip it with a precise mathematical semantics (Task 1).
2. **Equip MARVeLus with verification and simulation tools.** Verification will be achieved by discharging proof obligations to external theorem provers such as Satisfiability Modulo Theories (SMT) solvers, in the style of F* [120] and Frama-C [37]. Simulation will leverage decades of work around Ptolemy [109] and Zélus [28] (Task 2).
3. **Apply MARVeLus on relevant applications of CPSs.** We will focus our attention on the industrial system ACAS X for aircraft collision avoidance, and emergency braking and swerving maneuvers for automobiles, in collaboration with the Toyota Research Institute (Task 3).

This research plan will be complemented by an education plan where our research will be integrated and directly used by students at the undergraduate and graduate levels. We will also collaborate with the engineering program at a local middle school to enhance the students' understanding of the safety requirements of the systems they will engineer.

2 Career Goals and Strengths of the PI

My background is unique in that I have experience doing research in **programming language design and theory, as well as formal verification of practical cyber-physical systems**, such as the industrial airborne collision avoidance system ACAS X. I am therefore in an ideal position to bridge the gap formed between simulation and compilation of cyber-physical systems, and their logic-based formal verification, as illustrated in Fig. 1.

More automatic hybrid systems proofs. With my PhD student Nishant Kheterpal and undergraduate Eleanor Tang, I have developed an automated method for generating quantifier free formulations of obstacle avoidance that are efficiently machine-checkable [75]. Such formulations can be used in aerospace or ground robotics applications to provably check whether an object on a planned trajectory will safely avoid an obstacle on its route. This method automatically transforms a quantified statement of obstacle avoidance, which cannot be tested efficiently or verifiably because of the universal (for-all) quantifier. This method leverages geometric intuition and is the first known method to automate the generation of quantifier-free safe (collision-free) regions in this way. We plan on extending our method from planar collision avoidance to consider more general questions of reachability in three or more dimensions.

Verification of numerical methods. With my PhD student Mohit Tekriwal and undergraduate Joshua Miller, I have been working on verifying the convergence properties of numerical programs, that approximate solutions of differential equations. We have formalized in Coq the Lax-equivalence theorem to prove convergence of a family of finite difference schemes [123], then proved the convergence of solutions obtained from iterative algorithms [124]. We are currently working on formalizing implementations of those algorithms, taking into account floating-point arithmetic, using the tools VCFfloat [112] and VST [10].

Language Design. I have extensive experience designing programming languages for stream programming, verification of software-defined networks and home automation. Those past designs have many similar challenges to the design of the MARVeLus language.

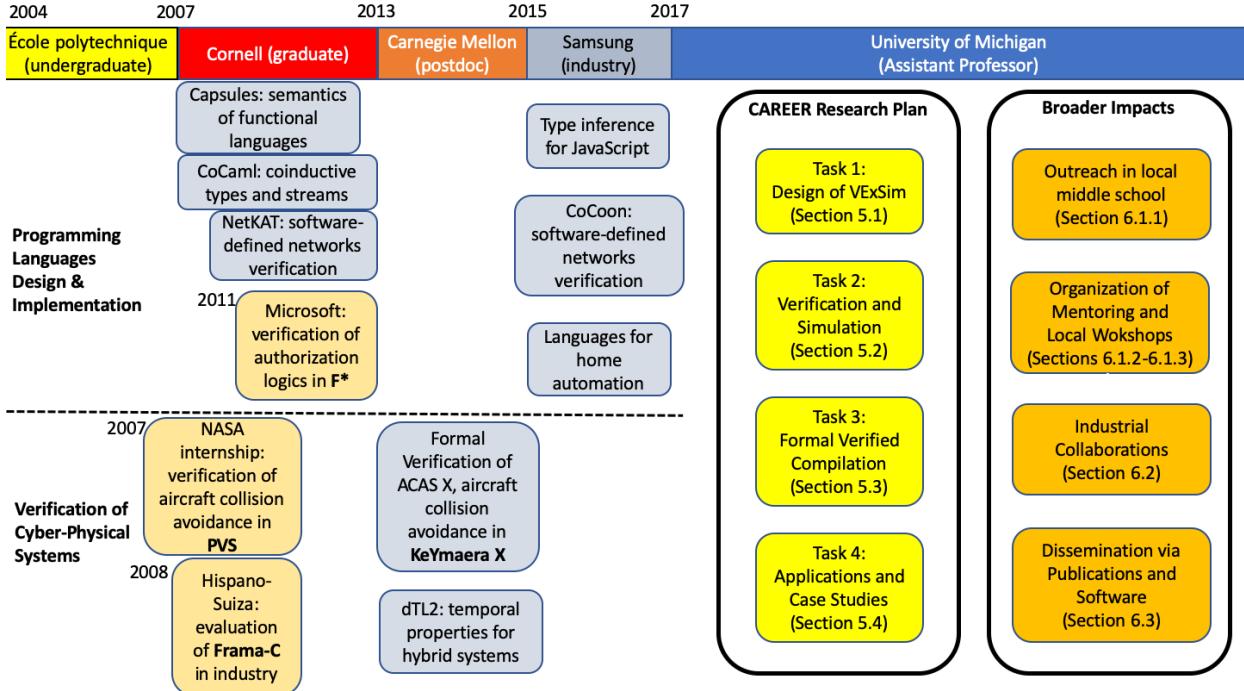


Figure 1: Overall career path and its relationship with the proposed work plan

Software-Defined Networking. Beyond stream programming, I have experience designing languages and verification tools for software-defined networking. Software-defined networking is a recent trend in computer networking that enables central management and programming of computer networks, leading to better performance and a decrease in hard-to-track bugs. I am a co-designer of the NetKAT language [8], which provides a sound and complete axiomatization of a programming language for computer networks, based on Kleene Algebra with Tests (KAT) [79]. I am also a co-designer of the CoCoOn language [115], which shows how to build correct by construction, software-defined networks.

Home automation. Finally, I have also co-designed the IoTa programming language for the automation of home tasks such as turning lights on and off or managing a thermostat [98]. IoTa comes with an internal checker that ensures that no two tasks can be contradictory or interact in undesirable ways, a common issue in home automation programming.

3 A motivating example: Formal Verification of Aircraft Collision Avoidance

As a motivating example, let us look at ACAS X, an industrial aircraft collision avoidance system. ACAS X is the Next-Generation Airborne Collision Avoidance System, destined to be installed on airliners as a successor of TCAS (Traffic Collision Avoidance System). Its development is funded by the Federal Aviation Administration as a response to a number of factors, including growing air traffic and the arrival of unmanned aerial systems (UAS). At the heart of ACAS X is a large table whose domain describes the current state of an encounter, and whose range is a set of scores for each possible action [76, 77]. The table is obtained from a Markov Decision Process (MDP) approximating the dynamics of the system in a discretization of the state-space, and optimized using dynamic programming to maximize the expected value of events over all future paths for each action [76]. Near-collision events, for example, are associated with large negative values and issuing an advisory is associated with a small negative value.

A few years ago, I, along with some collaborators, performed a verification of ACAS X using the hybrid systems theorem prover KeYmaera X [67, 68, 66]. Our approach abstracted away the large table by identifying and proving correct *safe regions* in the state space of the system where we prove formally that a particular

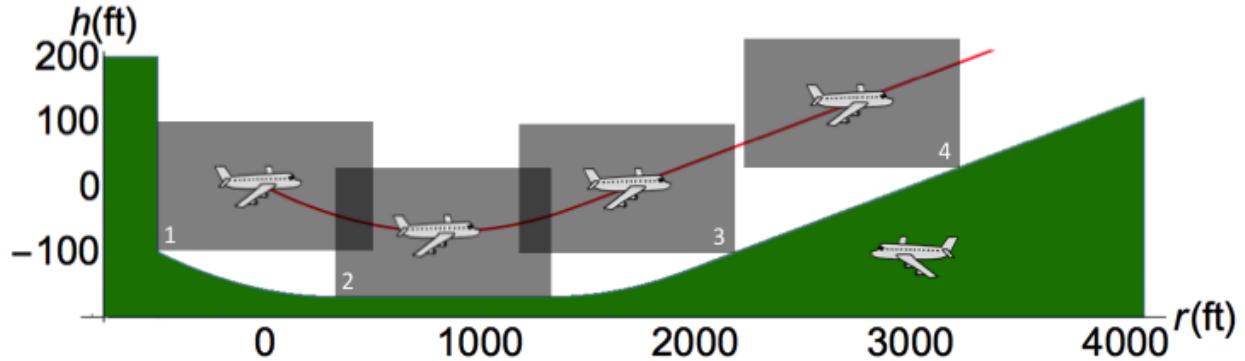


Figure 2: Safe region (shaded green) for an example “Climb 1,500 ft” advisory

advisory, if followed, prevents all possible Near-collisions from any aircraft position and velocity in that safe region (Figure 2). The work was successful and uncovered millions of individual bugs, some of which influenced later design decisions. However, after performing this verification, I realized that there was a discrepancy: the code that we verified consisted of a model (about 170 lines of code in KeYmaera X) along with an abstraction of the table (about 40 lines). But the code actually being executed consists of about 10,500 lines of Julia, along with a 994 MB table. We proved the abstraction of the table with great confidence. But, on the other hand, the 10,500 lines of Julia are quite far from or 170-line KeYmaera X model. **One of the goals of the MARVeLus project is to close this gap between verified code, executed code, and simulation code.**

4 Brief Overview of Related Research

4.1 Language and Tools for Cyber-Physical Systems

Synchronous languages such as Lustre/SCADE [56], Esterel [29] and Signal [84] are widely used in industry to create software for airplanes and cars, in part because they are capable of generating high assurance C code. However, based on discrete time, they do not allow the explicit modeling of a continuous environment. Nonetheless, they are a compelling success story with a wide use in industry, and an experience to build upon. Bourke et al. [25, 26] formally verified a Lustre compiler in the Coq proof assistant. In general, cyber-physical systems are notoriously difficult to design correctly [118].

The Ptolemy and Ptolemy II projects [39, 109] leverage the principles of design by contract to cyber-physical systems. The focus is on modeling, simulation, and design of concurrent, real-time, embedded systems, with comparatively very little work on formal verification, apart from a few exceptions using model-checking [34] or the Real Time Maude tool [100, 13]. Simulink [101] and Modelica [48] can simulate complete systems, including a continuous environment, and Simulink offers code generation without correctness guarantees. The Zélos language [28] builds upon the Lustre synchronous language and adds ordinary differential equations to simulate a controller in its physical environment.

On the verification end of things, seminal works by Artemov et al. [11] and Alur et al. [7] created a basis to reason about hybrid systems. Model checking has been adapted to reasoning about hybrid systems and hybrid automata [60]. Differential Dynamic Logic [104] extends Dynamic Logic [58] with differential equations to formally verify important safety and liveness properties of hybrid systems. SpaceEx [46] and CORA [6] explore reachability properties of hybrid systems with numerical approximations and zonotopes, enabling scalability. S-Taliro [9] and Breach [40] can find counter-example in Matlab/Simulink models. There are many approaches to generating invariants for cyber-physical systems, e.g., [52, 53, 117, 32, 33, 116, 113, 125, 55], and for synthesis of control algorithms [110, 111, 99].

Autocoding [73, 131, 130, 129] is an approach that compiles high-level code with formal proofs of good behavior, into low-level code. Although autocoding provides tools for verification and execution, it does not provide support for trustworthy simulation of the system. Other languages have recently been designed for

different specialized purposes: the Paracosm [89] language focuses on testing of autonomous driving systems, the PGCD language [16] on robot programming and verification, and the Scenic language [47] on scenario specification and scene specification for testing machine learning algorithms, especially vision. HyST [14] is a source transformation tool for hybrid automaton models, but does not provide a high level of abstraction to build large systems. Wongpiromsarn et al. [132] provide new conditions for periodic hybrid automata. Closest to this career project, Bohrer et al. [23] present an end-to-end verification of models verified in Differential Dynamic Logic. However their source language based on hybrid programs is fairly low level, lacks modularity, such as basic support for declaring functions, and compositionality, such as parallel composition.

4.2 Languages for Formal Verification

There is an enormous amount of previous work on languages and techniques for formal verification of programs, and it is impossible to list them all here. We will focus our discussion on logic-based approaches stemming from variants of Hoare logic or refinement types, since these are the techniques used in this proposal. Although we do not review it in detail for lack of space, there is also an extensive amount of work on verifying hybrid systems using temporal logics [107, 108, 91] and model checking [35, 15, 61].

The seminal works of Floyd [45] and Hoare [63] on assigning meanings to programs has been extended into dynamic logic [44, 58], the μ -calculus [78], and Kleene algebra with tests [8, 79]. Modern tools such as Dafny [85], Frama-C [37] and Krakatoa [43] use variants of these techniques at their heart. Dependent types [135, 12, 134] is an alternate approach to program verification, and its modern incarnations include the F* project [120, 121, 122], Dependent ML [133], Agda [30], and Zombie [31, 119]. Interactive theorem provers allow users to provide formal proofs of mathematical theorems, including proofs of programs. They include Coq [19], Lean [93], Isabelle [103], HOL and HOL Light [59], PVS [102], and others. Finally, the logic TLA [82] is specialized to reason about and formally verify protocols involving distributed systems.

I am very familiar with a variety of those tools. I have worked in the past with the KeYmaera X theorem prover [49, 68, 68] during my postdoctoral studies, the F* language [120, 65] at Microsoft Research, the PVS theorem prover [102, 62] at NASA, the Frama-C framework [37] in industry at Hispano-Suiza, as well as the Coq theorem prover [19, 123] and dynamic logic in recent projects [2, 3] (Fig. 1).

4.3 Aircraft Collision Avoidance

Many efforts have explored developing correct and comprehensive guarantees about collision avoidance decisions for aircraft and other vehicles. Collision avoidance algorithms are developed for both horizontal and vertical motion in 2D and 3D, and formally verified with PVS [95, 96, 42, 50]. In , The logic for the Traffic Collision Avoidance System (TCAS) is formalized in PVS and used geometries that generate advisories [94]. For the ACAS X system, [128, 83] analyze the state space of a similar MDP using probabilistic model checking and an adaptive Monte Carlo tree search. [97] uses a rigorous approach to construct a formally verified well-clear volume based on straight-line dynamics with no acceleration. Efforts that use a hybrid system model to develop safe horizontal maneuvers can be found in [51, 88, 106, 126]. The aforementioned results all verify a model of the considered system and of its software, and are thus unable to provide an end-to-end proof of correctness for collision avoidance. In contrast the MARVeLus language will enable such end-to-end proofs in the context of cyber-physical systems.

5 Research Plan

We will design MARVeLus, a *synchronous* programming language with *differential equations* and *refinement types*. The two most important influences will be the F* programming language [120] and the Zélus programming language [28], itself based on the Lustre synchronous language [56]. Although F* focuses on refinement types and Zélus on synchrony and differential equations, both languages are part of the ML family of languages [92, 87], and we are confident their designs can be integrated. Further influences, among others, will come from Dafny [85] and differential dynamic logic [104] for the verification part; Ptolemy [34] for the simulation part; and Esterel [29] and Signal [84] for the execution part. **The philosophy for MARVeLus**

can thus be summarized as “Zélos with refinement types”, “Lustre with differential equations and refinement types”, or “Synchronous F* with differential equations”. We expose refinement types and the verification engine in Task 2.1.

Throughout the design of the language, we will be particularly attentive to retain some level of compatibility with the SCADE suite [22, 41] (itself based on Lustre). SCADE is based on synchronous languages, and is widely used as a development platform for cyber-physical systems, including by large companies such as Airbus Commercial Aircraft and Airbus Space. This compatibility with the industry standard will be a key asset for industry adoption. Initially we will focus on ordinary differential equations with a certain degree of regularity (typically Lipschitz-continuity), ensuring existence, unicity and “niceness” of solutions. In the long run we will consider adding more complicated continuous dynamics such as differential algebraic equations.

MARVeLus is envisioned to be a realistic, practical, usable language with all the features expected of a modern programming language, e.g., constructs for abstraction and modularity. Even when not using refinement types, a strong typing discipline will be enforced to find bugs early on in the development process, and to ease the verification process, in the spirit of ML. We will first define the discrete part of MARVeLus (Task 1), then its continuous part (Task 2), then focus on Applications.

Thrust 1 – Synchronous Programming with Refinement Types

In this first task, we focus strictly on the *discrete* part of our language, and on the verification and execution.

Task 1.1 – Discrete MARVeLus: Syntax, Semantics and Simple Type System

In this first task, we will define discrete MARVeLus, without refinement types or verification capabilities. In our initial design for this discrete part (i.e., including streams but without differential equations), all expressions generate (infinite) streams of basic values (typically integers). The syntax of expressions is inspired by the discrete fragment of Zélos, which is itself inspired from Lucid Synchrone, an ML version of Lustre.

Most of the constructs, including λ -abstractions, applications, variables, (recursive) let-bindings and pair construction and destruction, are standard from ML. To this we add stream construction using the fbyconstructs of Lustre: given two streams $c = (c_1, c_2, c_3, \dots)$ and $e = (e_1, e_2, e_3, \dots)$, the stream c fby e has the same first element at c , and the rest of the stream is e delayed by one time step. The resulting stream is $(c_1, e_1, e_2, e_3, \dots)$. Throughout the development, we will be in constant contact with the Zélos designers (*see letters of collaboration from Marc Pouzet and Timothy Bourke*).

Preliminary Work. Streams, i.e., infinite list of elements, are an essential part of the design of synchronous languages. I have explored how to program rational coinductive types, including regular streams, using recursive and corecursive methods in the CoCaml language [69, 70, 71]. Along with related work on synchronous languages, this will help us understand the semantics of MARVeLus.

Task 1.2 – Type-refinement Specifications based on Signal Temporal Logic

Research Question: What is the right specification language for cyber-physical systems described in a synchronous language?

$b ::= \text{unit} \mid \text{float} \mid \text{int} \mid \text{bool}$	Base types
$\tau ::= b \mid \tau\{\phi\} \mid \tau \times \tau \mid \tau \rightarrow \tau$	Simple Types
$\mid \tau\{\phi\}$	Refinement
$e ::= c$	Constants
$\mid x$	Variables
$\mid \text{let } x : \tau = e \text{ in } e$	let-binding
$\mid \lambda x . e$	Function
$\mid e \ x$	Application
$\mid (e_1, e_2) \mid \text{fst } e \mid \text{snd } e$	Pairs
$\mid \text{if } x \text{ then } e_1 \text{ else } e_2$	Branching
$\mid \text{let rec } x : \tau = e \text{ in } e$	Recursion
$\mid e : \tau$	Type Annotation
$\mid c \text{ fby } e$	Streams

In many cyber-physical systems applications, traditional input/output specifications (e.g., à la Floyd-Hoare Logic) are inadequate. For example, in the case of airplane or car collision avoidance, we want to be able to express that “the vehicles did not collide throughout the execution” rather than “the vehicles are properly separated at the end of the execution”. The state-of-the-art in cyber-physical-systems verification typically uses Signal Temporal Logic (STL) [90]. STL is an extension of Linear Temporal Logic (LTL) where we can express properties about the timing of events. STL is widely used in industry (e.g. at Toyota), and is well-suited to reason about streams and continuous functions. In this task, we will design refinement types using expressions from STL. When completed successfully, this task will enable temporal properties about programs to be formally proved in MARVeLus, greatly enhancing the expressive power of the language.

Preliminary Work. I have designed two extensions of Differential Dynamic Logic, dTL² to reason with temporal operators [72], and more recently STdL to reason with STL specifications [5]. I expect that similar techniques will transfer to reasoning with refinement types. My students and I have devised an initial design for MARVeLus, including types, expressions and trace predicates, shown here.

$$\begin{array}{l} \text{Trace predicates } \phi, \psi ::= p \mid \neg \phi \\ \mid \phi \vee \psi \mid \phi \wedge \psi \\ \mid \phi \mathcal{U}_{[t,t']} \psi \end{array}$$

Task 1.3 – Foundations for a Refinement Type System for Discrete MARVeLus

Research Question: How to develop a sound and complete type system for a synchronous language with refinement types inspired from Signal Temporal Logic?

We will define a refinement type system for MARVeLus, along with a refinement-type checker. This allows us to leverage the existing type system to check base types and further refine it with our new typing rules. A simple example of a typing rule relates the `fby` expression operator with the \square temporal expression operator:

$$\frac{\Gamma \vdash c : b\{p\} \quad \Gamma \vdash e : b\{\square_{[0,t-1]} p\}}{\Gamma \vdash c \text{ fby } e : b\{\square_{[0,t]} p\}}$$

Intuitively, this rule says that if refinement p is true in both the initial state of c and everywhere in e up to time $t-1$, then it should be true everywhere in the stream c fby e up to time t .

Completeness. A desirable, foundational result of our refinement type system is its completeness, which we will seek to prove. We expect the completeness proof to use proof techniques coming from type theory, but also exploiting ideas from completeness results of axiomatizations of temporal logics.

Preliminary Work. Typing rules, their soundness and completeness will be inspired by our previous work on differential temporal dynamic logic [72, 5]. We have started developing a refinement type system for a stream calculus. Most constructs allow for relatively straightforward proof rules, but certain cases are more difficult, such as the if construct. A possible typing rule for an if statement is the following:

$$\frac{\Gamma \vdash x : \text{bool} \quad \Gamma, y : \{\text{int}:x\} \vdash e_1 : \tau\{\square\phi\} \quad \Gamma, y : \{\text{int}:\neg x\} \vdash e_2 : \tau\{\square\phi\}}{\Gamma \vdash \text{if } x \text{ then } e_1 \text{ else } e_2 : \tau\{\square\phi\}}$$

To prove that a property ϕ is true for a certain time (i.e., $\square_{[0,t]} \phi$), a possible rule for streams could be:

$$\frac{\begin{array}{c} \Gamma \vdash x : \text{bool stream} \\ y \text{ fresh} \end{array} \quad \begin{array}{c} \Gamma, y : \{\text{int stream}:x\} \vdash e_1 : \tau\{\square_{[0,t]} \phi\} \text{ stream} \\ \Gamma, y : \{\text{int stream}:\neg x\} \vdash e_2 : \tau\{\square_{[0,t]} \phi\} \text{ stream} \end{array}}{\Gamma \vdash \text{if } x \text{ then } e_1 \text{ else } e_2 : \tau\{\square_{[0,t]} \phi\} \text{ stream}}$$

However, the premises of this rule are too strong: the rule only allows to conclude if the condition (x , a stream of booleans) is identically true (resp. false) up to time t . But the rule does not allow to conclude anything in the

cases where the condition x is true only for some time steps. Essentially, we have a quantifier order issue: the rule says that something of the form $\forall t.A$ implies $\forall t.B$, but what we really want is the much stronger $\forall t, A$ implies B . Instead, we want to strengthen the rule to get something of a form similar to:

$$\frac{\Gamma \vdash x : \text{bool stream} \quad y \text{ fresh} \quad \begin{array}{c} \Gamma, y : \{\text{int stream} : x\} \vdash e_1 : \tau \{\square_{[0,t]}(x \Rightarrow \phi)\} \text{ stream} \\ \Gamma, y : \{\text{int stream} : \neg x\} \vdash e_2 : \tau \{\square_{[0,t]}(x \Rightarrow \phi)\} \text{ stream} \end{array}}{\Gamma \vdash \text{if } x \text{ then } e_1 \text{ else } e_2 : \tau \{\square_{[0,t]}\phi\} \text{ stream}}$$

In this new rule, because the condition x appears under the time quantification (embodied by the $\square_{[0,t]}$ construct), the time quantification is much stronger, as desired.

Task 1.4 – Implementation

We will implement the features described in the previous tasks, building a prototype of discrete MARVeLus. The implementation will be in OCaml, to leverage some features of the existing Zélus compiler, on which our initial implementation is based. In the long run, my plan is to integrate our development with the Zélus compiler, as this compiler already has significant industry traction, in particular among SCADE customers.

Verification conditions and SMT solvers. The verification will leverage existing verification techniques by identifying *proof obligations* in the program and proving them in a state-of-the-art SMT solvers [17, 38]. A satisfiability modulo theories (SMT) [21] solver is a solver combining a boolean satisfiability solver (SAT) with different theory solvers (about real numbers, integers, data structures, floating-point, etc.) to determine whether certain mathematical formulae are satisfiable. Identifying proof obligations and discharging to external solvers is a technique also used by e.g. F* [121], Liquid Haskell [127] or Frama-C [37]. We will primarily use the CVC5 SMT solver [17] as a primary back-end. A modern SMT solver with great performance, CVC5 also offers two great advantages for our purpose: it uses a new efficient variation of cylindrical algebraic decomposition for solving nonlinear real arithmetic as a theory, which will be particularly useful for verifying properties of differential equations [80]; and it supports proof production so that its proofs can be checked by another theorem prover such as Isabelle [18]. Finally, we can count on the CVC5 development team for support and collaboration on the project (*see letter of collaboration from Clark Barrett, one of the main designers of CVC5*). We will continue to support SMT-LIB-compatible SMT solvers by generating proof obligations compatible with SMT-LIB [20]. Importantly, we will focus on proof automation, and strive to avoid manual proofs of obligations in an interactive theorem prover, because of their often prohibitive human effort.

Preliminary Work. My group and I have started implementing verification capabilities in an initial design of MARVeLus. Our initial implementation extends the Zélus compiler, where we have added a compiler pass just after basic type-checking. This pass checks refinement types and generates proof obligations that are currently sent to the Z3 SMT solver [38] (we plan to switch to CVC5.) Our current implementation can currently prove simple examples, such as proving that, under adequate assumptions, a discrete version of a thermostat.

Thrust 2 – Incorporating Continuous Ordinary Differential Equations

In this thrust, we will add support for incorporating continuous dynamics in the form of ordinary differential equations (ODEs), along with refinement type rules enabling proofs of interesting properties on those ODEs.

Task 2.1 – A Refinement Type System for Differential Equations

Research Question: How to incorporate reasoning about ordinary differential equations, including continuous invariants, in a refinement type system?

Declaring variables following ODEs. Differential equations will be specified directly in the program, All differentiations will be made with respect to time, and we will not consider partial differential equations. Introducing an ordinary differential equation will be similar to introducing a recursive variable or stream. For example, to introduce a real variable x following the differential equation $x' = 4x + y^2$ with initial condition

$x(0) = 2$, the programmer will be able to write the declaration below, leading us to extend the possible expressions in the language with the `der` keyword (referring to the first derivative).

```
let der x = 4 * x + y * y init 2           e ::= ... | let der x=e init e in e | up(x)
```

Zero-crossings. The interface between the discrete and continuous parts of MARVeLus will be achieved using zero-crossings, inspired from the Zélus language. A zero-crossing $\text{up}(x)$ happens when the solution of a differential equation x crosses zero, spawning a discrete event. We will develop specific refinement typing rules to handle zero-crossings, as they define the interactions between discrete and continuous behaviors.

Reasoning about ODEs. We will introduce refinement typing rules to reason about Ordinary Differential Equations (ODEs). These rules will be inspired by some of the differential equations proof rules of differential dynamic logic. The MARVeLus language will be limited to Ordinary Differential Equations with time derivatives. For example, give the definition of x above, we would like to be able to prove that the variable x is always positive, which come down to proving that $x \geq 0$ is an invariant of the differential equation. Under the assumption that $x \geq 0$, we can prove that the derivative of x is also positive, and using a simple invariant rule, that x is always positive.

Completeness. Along with developing a Refinement Type System for the Differential Equation part of MARVeLus, we will extend our completeness of discrete MARVeLus to take into account the continuous dynamics. I expect this proof to follow similar arguments as the proofs of completeness of differential dynamic logic $d\mathcal{L}$, and its temporal counterparts $dT\mathcal{L}^2$ and $STd\mathcal{L}$, especially the complete proof theory of $d\mathcal{L}$ [105].

Task 2.2 – Different Compilation Modes for Simulation and Execution

Our compiler will allow for both simulation and execution of cyber-physical systems, using different compilation modes. However, in the case of execution, only certain parts of the program should be compiled, namely the parts that are not part of the environment. This leads to the following research question:

Research Question: How does the programmer specify and the compiler identify which parts of the program to compile for execution, and which should only be run for a simulation?

Program variables and environment variables. In MARVeLus, we model both the system and its environment. As such, every variable of the language can be: (i) either discrete or continuous; and (ii) executed by the system or an effect of the environment. Naively, one could think that discrete transitions are always executed by the system (software is typically discrete), while continuous transitions are effects of the environment's physical laws. While this is typical, it is not always the case: proportional-integral controllers are continuous (but often implemented in discrete software), while ball bounces can be modeled as discrete events. We will allow the programmer to specify whether each variable is part of the system execution (then it is compiled) or the environment (then it is not). This will be done as an annotation on the variable type.

Determinism and Nondeterminism. Closely related to the dichotomy between program and environment variables, lies the tension between determinism and nondeterminism. On the one hand, to be compiled and executed on hardware, a program needs to be deterministic, and the variables it uses need to have specific initial values. On the other hand, there is often uncertainty on environment variables. Finally, to simulate a nondeterministic program or an uncertain variable, a value must be chosen, typically sampled from a certain probability distribution. The default will be a uniform distribution but we will allow the programmer to specify different distributions for simulation purposes.

Real numbers and floating-point numbers. Physical variables in a physical environment should typically be represented by real numbers, while program variables representing real numbers are typically represented and compiled as floating-point numbers. For this reason, we distinguish real numbers of type `real`, from floating-point numbers of type `float`. (Of course floating-point numbers also come in different levels of precision.) The type system will ensure that real variables cannot be program variables that would be compiled.

Based on my verification experience [68, 123], it is often easier to carry out formal verification by making the simplifying assumption that floating-point numbers behave as if they were real numbers. Many verification conditions become simplified (e.g., overflows do not have to be dealt with), making the verification task more tractable. In MARVeLus, we will introduce a compilation flag conflating reals and floats for verification purposes. Of course, this simplification comes at a cost: if an unexpected event such as a floating-point overflow happens, then the guarantees of the verification are not valid anymore. A similar distinction exists between (mathematical) natural numbers and machine integers. Mathematical natural numbers cannot overflow, and are e.g. represented by the type `nat` in Coq. We give the type `nat` to natural numbers and the type `int` to integers to mark this distinction, and we will also include a flag to conflate them for verification as desired.

Preliminary Work. Although I do not have preliminary work directly related to this task yet, in the past I have worked with collaborators on Dynamic Code Splitting for Javascript [54]. In that work, we allow the programmer to write a web application by writing just one program in Javascript, and our compiler automatically partitions the executable code in a client side and server side, adding explicit communication when needed. We expect the kind of code analysis of our Javascript work to be relevant in determining which part of the program to compile to hardware (for execution), and which part to simulate (for simulation).

Task 2.3 – Formally Verified Simulation

Research Question: How to provide guarantees on the simulation of a cyber-physical system?

The simulation of dynamical systems that use ODEs typically rely on unverified, off-the-shelf numerical algorithms to approximate the solutions of those ODEs. For example, the Zélus tool uses Matlab’s `ode45` built-in function. Because those tools are unverified, there is no guarantee that the numerical solution of the differential equation is correct within a known error bound. Adapting and extending recent work on formally verified numerical methods [123, 124], we will develop tools to obtain formal guarantees on the approximated solutions of differential equations. We will be able to guarantee that the simulated traces are actually traces of the model, within a known, formally verified error bound. Even if we do recognize that a simulation can only be as good as its model, we believe that there is value in guaranteeing that a trace is a valid trace of a model, and in bounding its numerical error.

Integration with Verified Compilation. As a stretch goal, we will integrate our formally verified simulation of differential equations with an existing formally verified compilation framework for Lustre [25, 26]. We will work with the authors of the framework, and this will provide a full, discrete-and-continuous, verified simulation of cyber-physical systems (*see letters of collaboration from Marc Pouzet and Timothy Bourke*). The formal guarantee we will provide is that the generated simulation trace is actually a trace of the model, within a known error bound.

Preliminary Work. We have already formalized certain results pertaining to numerical methods for finite difference schemes [123], as well as iterative methods for approximating the results of linear systems [124].

Task 2.4 – Implementation

We will extend discrete MARVeLus to handle differential equations following the extended refinement type system. We will also generate proof obligations that will then be sent to the CVC5 SMT solver. For this part, we will particularly need the benefits of the nonlinear linear arithmetic solver of CVC5 [80].

Thrust 3 – Applications and Case studies

To guide the development of MARVeLus and ensure that the design decisions are adequate, we will use the language on three kinds of applications: a ground robot and a quadcopter in the lab; an industrial application for ACAS X aircraft collision avoidance; and as a homework in a graduate class with a verification module.



Figure 3: The M-Bot Mini Ground Robot and the M-330 Quadcopter, used in my laboratory for running MARVeLus on hardware

Task 3.1: Small ground robot: the M-Bot Mini Ground Robot

Research Question: How to enable MARVeLus verified execution and simulation on a small ground robot in the laboratory?

We will run and evaluate MARVeLus on a small differential-drive wheeled robot, the M-Bot Mini (Figure 3). M-Bot Mini is equipped with on-board sensors including a 9-axis inertial measurement unit (IMU), a rotating LiDAR, and a front-facing optical camera. The drivetrain consists of two geared DC motors. The robot is equipped with a Beaglebone Blue, a Linux-capable single-board computer featuring built-in motor controllers. We will focus on verifying collision avoidance properties. Running MARVeLus on real hardware will give us crucial insights into the design of the language, and as to the limits of the verification guarantees.

Preliminary Work. We already own and operate two M-Bots Mini in my laboratory, and we are able to run simple MARVeLus code (move forward and backward, simple turns). The MARVeLus runtime can be configured to run remotely on a separate computer, or locally on-board the robot's Beaglebone Blue. In the former configuration, the computer running the MARVeLus runtime and user code communicates wirelessly with the robot over the WLAN network and delegates sensor and actuator actions to the robot when needed. This configuration enables easier debugging, including substituting the robot with a simulator for offline development. In the latter configuration, the MARVeLus runtime and user code execute directly on the robot which allows for reduced communications latency. In both configurations, the MARVeLus runtime communicates with the controller code via the Lightweight Communications and Marshalling (LCM) protocol.

Task 3.2: Flying robot: the M-330 Quadcopter

Research Question: How to transfer the knowledge gained on a ground robot to an autonomous quadcopter?

We will also run and evaluate MARVeLus on the M-330 Quadcopter (Figure 3), first focusing on quadcopter collision avoidance properties. As with the M-Bot Mini, a Beaglebone Blue serves as the main compute module onboard the M-330, where its wireless communications, real-time capabilities, and sensors allow for a highly integrated, easily configurable flight controller. Having a common compute platform between robots in our project means that much of the core MARVeLus functionality can be shared, allowing us to concentrate our development efforts on platform-specific features. Along with the sensors on the Beaglebone Blue, the quadrotor can also be equipped with reflective targets to make use of motion capture.

Preliminary Work. We already operate an M-330 Quadrotor in the laboratory. Our recent paper on quadcopter collision avoidance [4] provides safety regions, formally proved in the KeYmaera X theorem prover.

Implementing those safe regions with real hardware will show us how applicable this proof is with actual hardware components and physics.

Task 3.3: Aircraft Collision Avoidance and ACAS X

Research Question: How to provide a verified and executable implementation for the ACAS X collision avoidance system?

In this task, we will close the gap between verification, execution and simulation on ACAS X, the initial motivation for the MARVeLus project. Thanks to my past verification work on ACAS X, I have a deep understanding of the intricacies of the system and its verification challenges. We will build a new implementation of ACAS X using MARVeLus, equip it with the differential equations modeling simplified flight dynamics, and perform an end-to-end verification of ACAS X in MARVeLus. As a stretch goal, we will aim to make our verified implementation a alternate reference implementation of ACAS X (the current reference implementation is unverified and in Julia). Throughout this case study, I will leverage past interactions with different actors of the ACAS X project, including with the Federal Aviation Administration and the main designers of ACAS X.

Preliminary Work. Beyond our verification work of a hybrid-systems model of ACAS X [67, 68, 66], we have recently introduce an automation technique using active corners that will simplify the proof [75].

Task 3.4: Incorporation in AERO 552 Aerospace Information Systems

Research Question: How to ensure graduate students and engineers can use MARVeLus effectively?

In my graduate class AERO 552 on Aerospace Information Systems, one module is dedicated to formal verification. The current associated homework is purely theoretical, and lacking hands-on experience. Once a stable prototype of MARVeLus is built, I will incorporate the use of MARVeLus in two homeworks, so that students can understand how to use verification tools in practice. The case study will be a simplified version of our ACAS X work, where we envision to use very simplified dynamics. As an added advantage, the incorporation in AERO 552 will give us a first set of users, which will help us identify shortcomings in terms of usability and performance. This will be very useful for the development and evaluation of MARVeLus.

6 Evaluation Plan

Our evaluation plan is three-fold: experiments on small robots in the laboratory (tasks 3.1 and 3.2), programming of ACAS X (tasks 3.3), and finally use of the MARVeLus language in class with graduate students (task 3.4).

Industry adoption. Finally, an essential part of our evaluation will be the technology transfer to industry. Through our collaborations with the different industries I have established collaborations with the Toyota Research Institute, Raytheon/Collins Aerospace, the National Aeronautics and Space Administration (NASA), and Amazon Web Services, through past or present funding provided by those entities (*see letters of collaboration from Ebad Jahangir at Raytheon and Aaron Dutle at NASA*). I have visited Toyota and Raytheon/Collins each multiple times, and am spending a week at NASA Langley Research Center in July 2022. I will use those collaborations as a source of inspiration for relevant problems, and as a source of challenges and relevant industrial applications.

7 Implementation Plan and Timeline

The timeline of the proposed work including some of the milestones is given below.

7.1 Timeline

Table 1 shows a timeline of our proposed work.

#	Thrust / Task	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5
Thrust 1: Synchronous Programming with Refinement Types						
1.1	Discrete MARVeLus: Syntax, Simple Type System	■				
1.2	Type-refinement Specifications based on SLT		■			
1.3	Foundations of a Refinement Type System			■		
1.4	Implementation			■		
Thrust 2: Incorporating Continuous Ordinary Differential Equations						
2.1	A Refinement Type System for Differential Equations	■				
2.2	Compilation Modes for Simulation and Execution	■	■			
2.3	Formally Verified Simulation		■	■		
2.4	Implementation	■	■	■	■	
Thrust 3: Applications and Case Studies						
3.1	Small Ground Robot: the M-Bot Mini Ground Robot	■	■			
3.2	Flying Robot: the M-330 Quadcopter		■	■		
3.3	Aircraft Collision Avoidance and ACAS X			■	■	
3.4	Incorporation in AERO 552 Information Systems	■	■	■	■	

Table 1: *Proposed project timeline. Each task is marked with a box for each quarter that we expect it to be active. Quarters marked with a “■” indicate a tentative software release in that quarter.*

8 Risks and Mitigations

9 Broader Impacts

9.1 Integrated Education and Outreach Plan

Educating students to design and program correct cyber-physical systems is important at all levels, from middle school to graduate school. Our education plan targets three populations: middle school students for an initiation to safety and verification, late-stage undergraduate students and early-stage graduate students through the organization of mentoring workshops, and early-stage to established graduate students through the organization of the Midwest Programming Languages Seminar.

9.1.1 Collaboration with Title 1 middle school in Detroit suburb

I will collaborate with Samantha Coram and Sabrina Cristofaro, science teachers at Ferndale Middle School, at Title 1 school in Ferndale, Michigan, a suburb of Detroit (*see collaboration letters*). The school currently has 499 students enrolled, including 56% Black or African American, 31% White, and 13% from other races. 76% of students qualify for free or reduced lunch. Ferndale middle school is also a School of Choice, attracting students from every part of Ferndale, but also from the neighboring cities of Oak Park and Hazel Park, also suburbs of Detroit. The school is a 45-minute drive from the campus of the University of Michigan.

Samantha Coram and Sabrina Cristofaro are currently teaching science following the Project Lead The Way [1] curriculum in 7th and 8th grade. The class meets 5 days a week throughout the semester. We will collaborate in the “Design and Modeling” class to enhance the student’s awareness with safety of critical systems, and familiarize the students to the concept of verification. Projects in their class focus on providing tools for children with cerebral palsy, a congenital disorder marked by impaired muscle coordination.

During each semester of the five years of the project (ten semesters total), my Ph.D. student and I will come to Ferndale middle school once a week for four weeks, for each semester (\$2,000 of the budget was allocated to travel to the school). I will first give a presentation regarding safety and verification, targeted to middle schoolers, followed by some hands-on experience on a simple prosthetics project for children with cerebral palsy. The presentation will show the students how to use simple geometric arguments from their mathematics class to develop conditions ensuring that the prosthetics does not harm the patient by e.g. overbending some

muscles, or moving too fast or with too much force. Together with the teachers, I will then show them how to implement those conditions, and the students will be able to test them in their lab (on a mannequin) after 3D printing the prosthetics. The hands-on experience will be done in collaboration with my graduate students, giving the middle school students a chance to discuss, interact, and establish longer-term connections with graduate students. The end goal of the project is to give students a greater awareness of the importance of safety in designing systems, and the realization that scientific tools exist to ensure this safety. \$5,000 of the budget is allocated to the purchase of 3D printers and robotics motors, which will be essential to the successful completion of this project, as it will allow students to test their concept in physical life.

In the long run, Samantha Coram, Sabrina Cristofaro and I will establish new orientations and objectives of the class. We will be able to give back to Project Lead The Way so that safety and verification can be introduced to middle school students across many more schools across the country. A focus on safety early on is becoming increasingly important as some of those students will grow to become the engineers and designers of the prosthetics, delivery drones and self-driving cars of tomorrow.

9.1.2 Organization of Workshops

Organization of Verification Mentoring Workshops. I have a history of organizing mentoring workshops, especially targeted to underrepresented minorities. I was an organizer in 2020, and a co-chair in 2021, of the Verification Mentoring Workshops (VMW). VMW is a workshop for students held the first two days of the Computer-Aided Verification (CAV) conference, whose purpose is to provide mentoring and career advice to early-stage graduate students and late-stage undergraduate students. The workshop particularly encourages participation of women and underrepresented minorities. Due to the pandemic, both workshops were held online, an opportunity to serve many more participants. Each workshop attracted more than 400 registrants, and over 50 participants at each session. In 2020, 22% of the registrants identified as female, 0.7% as nonbinary, 1.4% as Black, African or African-American, and 0.7% identified as Hispanic. In the long run, I am planning to stay involved in the organization of mentoring workshops, including both VMW and PLMW.

Organization of the Midwest Programming Languages Summit (MWPLS). I am organizing the 2022 MWPLS, a regional workshop offering a friendly venue for graduate students of all backgrounds to present in-progress work. We particularly encourage presentations from women and students from underrepresented minorities, and students who are still early in their studies.

9.2 Undergraduate Research

I am dedicated to broadening participation in engineering education. I have hosted over fifteen undergraduate researchers in my group, including 3 women, and I regularly recruit through the Summer Undergraduate Research in Engineering (SURE) program. Five of the mentored undergraduates have written papers [3, 2, 4, 74, 75, 64], one went on to a Ph.D. program and another to a masters program. Over the last three summers, I have also hosted four Ethiopian students from the Addis Ababa Institute of Technology (AAiT), through the African Undergraduate Research Adventure (AURA) program. One of them is now a Ph.D. student in the US, and two others are applying for Ph.D. programs.

9.3 Graduate Education and Research

I teach the graduate course AERO 552: Aerospace Information Systems, where I will introduce homeworks using MARVeLus (see Task 3.4). I already offered this graduate course four times in Fall 2017, Winter 2019, Winter 2021 and Winter 2022. Most of the funds requested for this project will be used to support a Ph.D. student. I currently advise or co-advise four graduate students: one in Aerospace Engineering, one in Computer Science and Engineering, and two in Robotics. I will primarily recruit students from those programs.

9.4 Undergraduate Education

I have created a completely new class AERO 350: Fundamentals of Aerospace Computing. This junior-level class gives students a firm understanding of the use of computing in aerospace engineering, including fundamentals of programming, computational science and embedded systems, and an introduction to verification. I

have taught the class 4 times (Fall 2018, 2019, 2020, 2021), and it has been a success with an average score of 4.2/5.0. The class is now mandatory for all undergraduates in Aerospace Engineering.

9.5 Dissemination via Publications and Open-Source software

The results of this multidisciplinary project will be published in the venues four different communities: programming languages (POPL, PLDI, SPLASH), cyber-physical systems (HSCC, ICCPS), verification (CAV, TACAS, IJCAR), and embedded software (EMSOFT). Starting the third year, I will organize tutorials at the HSCC and SPLASH conferences to bring together the programming languages and cyber-physical systems communities. I will especially encourage participation from my industry collaborators. The software from this research program will be released under the modified BSD license, and disseminated through GitHub.

10 Results from Prior NSF Support

Jean-Baptiste Jeannin: #2219997: FMitF: Track I: Foundational Approaches for End-to-end Formal Verification of Computational Physics, \$750,000, 10/01/22-09/30/26. PI: Jean-Baptiste Jeannin, co-PI: Karthik Duraisamy. **Intellectual Merit.** Numerical solutions of differential equations are widely used in science and engineering. This simulation process involves errors and uncertainties, that we seek to quantify and formally prove correct. The current state of the art in numerical analysis relies on paper proofs; in contrast our proofs are mechanically checked in an interactive theorem prover. **Broader Impacts.** The proposed activities – centered around formal verification – have the potential to re-invigorate existing links between theoretical computer science and computational science. Our work will open a new space of physical applications to formal methods researchers, and for computational physicists to see the value in formalizing their programs.

[JB: Some general remarks / questions:

- Are there too many applications (currently five)? Currently I have two in the lab (M-bot ground robot, quadcopter), two industrial (airplanes ACAS X, cars, both extensions of previous work), and one in class. If I had to pick 3, I would probably just do the ground robot, ACAS X and the class. Should I just focus on those 3?
- I have dropped the part about verified compilation; I only mention it in passing. I would be nice to have, but after several feedbacks regarding it, I think it's too much for this grant which is essentially the same budget as an NSF Small. Plus the Zélos team has done most of it already.
- On the ACAS X example, the core of the verification involves a lookup table. I don't talk explicitly about how to deal with lookup tables, but I make ACAS X a front-and-center case study.
- Is providing a verified reference implementation for ACAS X too ambitious? At the same time we have 5 years, and it's a really nice, applicable case study.
- do we keep simulations? After all most of the work is verif+exec, whereas simulation piggy-backs on the work done already by Zélos. The only work that is really doing simulation is the relationship with Coq proofs of numerical methods for ODEs.
- In the past Wes has suggested human studies. I am not sure if it's a good idea, especially because I've never done it, hence low credibility in actually implementing them, and I would have to get some pointers on how to do it specifically.

]

[JB: High-level feedback from NSF reviewers that I have tried to address:

- Not enough details – needs much more meat
- No Evaluation Plan

- Add concrete examples

]

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