Co-design of Structure and Intelligence for Embedded System Optimization

PROPOSAL TO THE NORTHROP GRUMMAN – UMD SEED GRANT PROGRAM

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Abstract

A challenge in modern engineering is to design complex embedded systems with task specifications in a rigorous way with guarantees on correct operation, and optimization of relevant implementation metrics, including processing speed, power consumption, and memory requirements. We propose to develop foundations for automated synthesis of embedded agents, and aerial robotics in particular. Given a set of tasks and constraints on the size, weight and power of the quadrotor, we propose to develop models and methods for synthesizing the quadrotor platform. This includes the integrated selection of sensing and embodied processing devices; the development of algorithms for control and signal processing, which we study in the spirit of Active Perception as a coupled entity; and the autogeneration of optimized software for embedded devices. The developed algorithms and synthesized software will be designed to reliably carry out a specified mission under given constraints, and to adapt autonomously based on changing characteristics in the operational environment. Through the novel models, methods and simulations developed in this seed project, we will develop preliminary results and interdisciplinary experience to support proposed new research on algorithms and software tools for automated synthesis and optimization of embedded agents.

1 Context

The design of autonomous aerial vehicles such a quadrotors requires many inter-related competencies, including the choice of the aerial vehicle's structure and sensors; development and tuning of algorithms for sensor signal processing and knowledge extraction; and design and implementation of embedded software that coordinates and executes these algorithms. Conventional design methods integrate these competencies using ad-hoc methods without systematic analysis or optimization of the coupling across them. This leads to significant underutilization of technologies, including machine learning techniques, sensors, actuators, and embedded processors, resulting in devices that are significantly larger, less power efficient, and provide less capability and less reliability compared to what the underlying technologies and theory have the potential to provide. Additionally, the ad-hoc design and integration processes greatly increase the turnaround time to incorporate new technologies, which slows down advancement of the state-of-the-art in aerial vehicle systems.

2 Intellectual Merit

To address the problem motivated in the previous section, we propose a holistic investigation into the design and implementation of autonomous aerial vehicles. In particular, we propose to develop algorithms, methodologies and software tools for the design of quadrotors with different size and task constraints that jointly consider the physical characteristics of the sensing devices, and embedded processing devices, along with embedded software characteristics of the algorithms for machine learning, control and signal processing, as they are realized on the embedded processing hardware. This multidimensional optimization problem encompasses different strata, including hardware, integrated chips, sensors, effectors and software – the set of programs running on the system, the representations computed by these programs, and their efficient and reliable implementation on the processing hardware.

Holistic system modeling and optimization across these strata is a new research area that has the potential to lead to disruptive design methodologies and tools for aerial vehicles that serve mission-critical applications. We call this field "Embodied AI". While we propose to study Embodied AI in the context of aerial vehicles, the concept has much broader applicability to other types of cyber-physical systems.

We are interested in creating quadrotors with perception that autonomously perform tasks in different environments. The current approach in Robotics is to use Computer Vision modules that aim to build a 3D representation of the scene that is of general utility, generally with the so-called simultaneous localization and mapping (SLAM) approach. Using this representation, tasks are planned and accomplished to allow the quadrotor to demonstrate autonomous behavior. However, SLAM approaches are computationally very expensive, and inefficient for aerial robots. To solve many tasks, we don't need accurate 3D models.

We can take inspiration from biology. Insects and birds have solved the problem of navigation and complex control without the need for building accurate 3D maps of the scene. Their solutions are task driven. Biological systems have developed through evolution, and in this process their hardware (body, and sensing devices) and software (brains) have co-evolved. For example, bees have compound eyes, with a large field of view but of low resolution, which are suited for high speed navigation with low computational cost — as is evident from the small amount of neurons in the bee's brain. Birds of prey, such as the eagle, have large field of view eyes but also accurate vision to achieve both agile flight and accurate recognition and tracking of prey, and this requires much larger brains. Similarly, in the engineering domain, while sensors like LIDAR, RGB-D cameras or stereo cameras can make depth perception easier, they may not be feasible on smaller robots due to Size, Weight, Area and Power (SWAP) constraints. Instead simpler representations when coupled directly with the control of the drone may be sufficient to solve certain tasks. For example, we may not need depth, but only image motion from lightweight cameras to avoid obstacles.

The most distinguishing aspects of this research stem from our interdisciplinary collaboration across the areas of computer vision, robotics, and embedded signal processing. In our work on platform-aware algorithms, and parameterized libraries of algorithmic modules, we will build on our experience in computational motion analysis and visual servoing (e.g., see [1, 2, 3]). In our work on tools to map algorithms onto embedded processors, and run-time techniques to coordinate algorithm configurations and hardware subsystems, we will apply our experience in model-based architectures and design tools for signal and information processing systems (e.g., see [4, 5, 6]).

3 Technical Approach

The goal of this work is to develop a framework for co-design that describes aerial robotic design problems, defined as tuples of "functionality space", "implementation space", and "resources space." To make the problem solvable, we will impose constraints on the resources: the SWAP constraints (such as the maximum size, weight and configuration of rotors) and constraints on the computing resources (maximum available memory). Given a set of tasks (functionality), we then can ask: *a) Is an implementation (involving software design and realization in embedded hardware) possible? b) What is the implementation using minimal amount of information to solve the tasks given the resource constraints?*

Technical work involves: a) the design of the drone hardware and sensors and the development of algorithms using the information from the sensors to achieve a set of mission tasks; b) the realization of these algorithms in embedded processors and development of tools for the design and implementation of these multicore machine learning and signal processing applications. Integrated modeling, analysis and optimization across the different components is a major distinguishing aspect of our proposed research

Figure 1 illustrates the new design methodology that will be developed in the proposed project for the specific Embodied AI application area of Drone-Level Codesign. Major research efforts and deliverables of the project are represented by the blocks labeled Platform-aware algorithms, Parameterized libraries of algorithmic modules, Tools to map algorithms onto embedded processors, and Run-time system to coordinate algorithm configurations and hardware subsystems. Our research will center around the integrated development of novel algorithms, libraries and software tools across these project components.

As a unifying formalism to promote systematic analysis and optimization across the developed algorithms, libraries and tools, we will apply the paradigm of dataflow-based modeling of signal and information processing systems (e.g., see [5]). Dataflow is widely-used in commercial, domain-specific tools for signal and information processing, such as LabVIEW by National Instruments, SystemVue by Keysight, and TensorFlow by Google. Our prior research has influenced significant aspects of important commercial dataflow tools (e.g., see [7, 8]). However, revolutionary and strongly interdisciplinary advances are needed to dataflow methods to address the complex challenges described in Section 1. We will develop such advances as a core component of this project. More specifically, our project will lead to new fundamental understandings among the areas of dataflow, machine learning, and cyber-physical system design. The results of the proposed seed project will help to demonstrate our proposed vision of Embodied AI with concrete simulation experiments in the context of Drone-level Codesign.

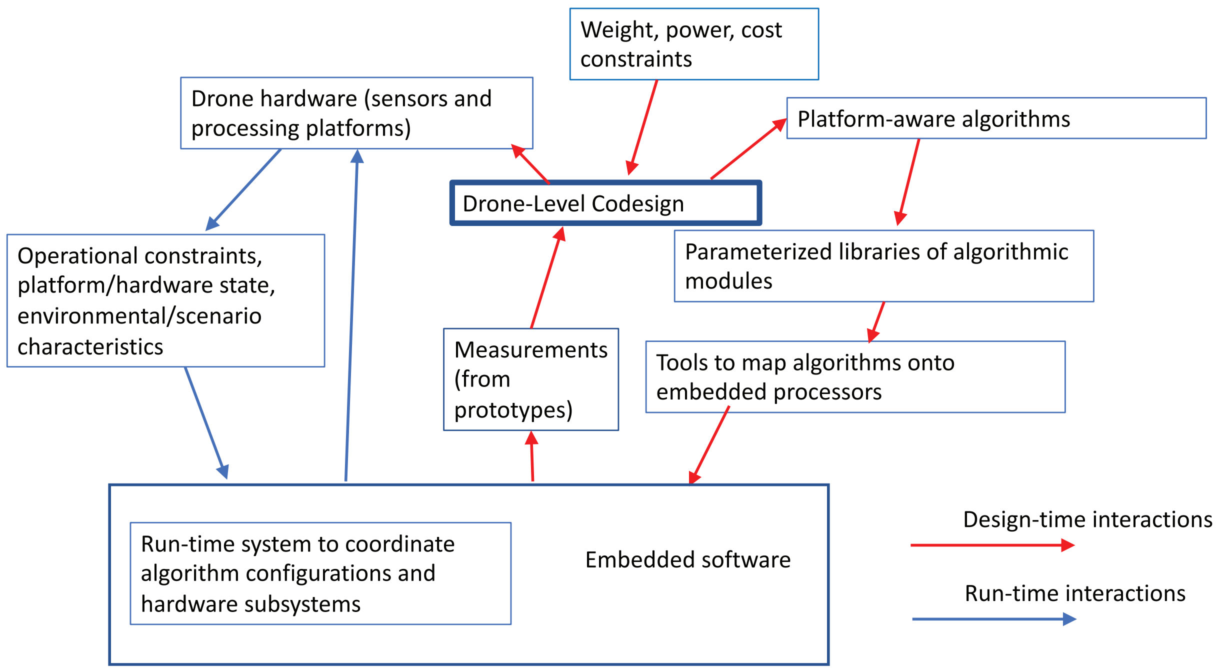

Figure 1: An illustration of the proposed new design methodology for Embodied AI.

4 Alignment with Goals of Seed Grant Program

This seed project is aligned with the topic entitled *sensing, advanced analytics, and/or responses to optimize embedded systems*. Through our new models and methods for Embodied AI, we will systematically integrate and optimize resource, and accuracy-aware machine learning methods to enable much smaller, more power efficient, and more reliable implementation of autonomous aerial vehicles compared to what is possible using conventional design methods. We will demonstrate these approaches through the design of smaller quadrotors and new nano-quadrotors capable of monitoring the environment and performing delivery tasks in a local environment. Their advantages over larger quadrotors are due to safety, agility and power efficiency. Smaller quadrotors are safer to humans, other beings and the environment, inflicting no or minimal damage upon collision. They are more agile because of smaller moment of inertia, which makes their reaction to environmental factors faster.

The proposed seed grant would allow jump starting collaboration between the two PIs, Bhattacharyya and Fermüller, and linking this collaboration to technical problems of relevance to Northrop Grumman. The PIs both have significant experience in interdisciplinary, multi-investigator collaborations, but have not worked together before on joint research projects. The seed grant would enable development of preliminary results that would allow the PIs to more effectively pursue funding opportunities at relevant agencies. Furthermore, research in collaboration with Northrop Grumman will help to strengthen the proposals and research in terms of impact to industry and defense.

5 Potential for Leveraging Proposed Work

The proposed work integrates aspects of machine learning, cyber-physical systems, computer vision, and electronic design automation. The unique interdisciplinary nature of this work is enabled by the highly complementary expertise of the investigators. The theme of the work provides significant potential for projects in major funding agencies, including AFOSR, DARPA, and NSF. The relevance to aerial robotics, embedded artificial intelligence, and cyber-physical systems, are major areas of interest at these agencies. Specific examples of relevant proposal targets include DARPA's OFFSET BAAs and Tactile Technology Office BAAs, and NSF's National Robotics Initiative and Cyber-Physical Systems Programs. We will build on the preliminary results and interdisciplinary experience enabled by this seed grant to pursue funding opportunities at funding agencies such as these.

PI Bhattacharyya and Fermüller are both US Citizens, which provides potential to collaborate with Northrop Grumman on a broader variety of topics, including those with citizenship restrictions.

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