Proposed Research: "How should one choose an optimal computational architecture for implementing sensor-based perception with real-time constraints?"

Keywords: robotic perception, parallel computation, embedded networks, system optimization

Research in robotic applications is rapidly making progress in enabling robots to navigate natural human environments. Computer vision algorithms and sensor fusion techniques promise to eventually allow robots to work side-by-side with people by turning streams of sensor data into a viable model of the world that has feature sets which we consider important. A critical aspect of this perception task is combining the data from several different types of sensors into a coherent representation of the work environment fast enough to enable relevant and safe decisions to be made by planning algorithms. From my experience designing robotic components and systems, I know that choosing the right hardware for a computational task is critical to the success of a project. What is not obvious is which of the many available options for hardware will be best suited for a particular task in terms of effectiveness, flexibility, and cost. I will study how the computational requirements for processing sensor data motivate selection of an architecture, and work towards a method for choosing the optimal hardware for a task.

First, I will need to better understand the state-of-the art techniques in computational system design and optimization, as well as robotic sensor fusion and perception. I already have experience with designing robotic systems using dedicated real-time microcontrollers, embedded system networks, and FPGAs. Through graduate courses and an extensive literature search, I plan to strengthen my formal understanding of designing around these systems and extend my understanding of new computational developments such as specialized Graphics Processing Units (GPUs) and logic based neural networks. I will also need to become and expert in using the pertinent algorithms being used to combine the visual, odometry, and other specialized sensor data commonly used by robots, and the applications that motivate the choices of sensors and algorithms. From my undergraduate study and research staff projects, I have developed a good intuition for the ways that robotics systems approach the implementation of sensor filtering and fusion. A prime candidate approach employed by many current robotics projects[1] is fusing sensor data with an Extended Kalman Filter. By continuing to study advanced data processing techniques I will gain insight into potential ways to improve overall performance by implementing perception techniques on novel architectures.

To answer the core research question of how algorithmic requirements motivate architectures I will analyze both the commonly used algorithms and architectures. I will target analysis of algorithms that are effective in theory but take far longer to compute than is necessary for producing results in a useful amount of time. I anticipate that using a version of asymptotic analysis with special considerations for data throughput and requirements on latency specific to robotics domain problems will shed the most light on algorithm performance on each hardware type. Several advances have already been made in adapting these analysis tools to parallelized[2] and networked[3] hardware, and I hope to leverage that research to improve my analysis of perceptive tasks. A preliminary output of this exploration should produce different classes of sensor data processing problems. I expect a spectrum of algorithms will emerge, from those that are best implemented on sequential processors, to those that stand to gain the most from being implemented on massively parallel architectures such as FGPAs and GPUs. Somewhere in the middle will be algorithms that are most effective on networked embedded systems that take advantage of local specialization and general cooperation. A primary output of this phase of research will be an abstracted parameter set for perception tasks that can be used to quantify aspects of the algorithms such as minimum critical computation path, degree of data sharing between different sensor types, and parallelizability of algorithms.

As my research triages algorithms into regions of ideal computational architectures, I will collect performance data after implementing representative algorithms on different computational architectures. Ideally, this would involve modification of a current robotic project that has demanding sensor processing tasks, such as visual odometry for simultaneous localization and mapping. If this phase is not implemented on a robotic system I will at least use published data sets collected from robots deployed in the field to test the implementations. By comparing the parameterizations of algorithms to the traits of the different processing architectures, I will be able to draw conclusions on what aspects of perception algorithms should motivate the selection of a processor architecture type. I will also be able to produce optimization tools that can analyze a perception task to provide minimum required specifications for the designated architecture type. Collecting this information and reporting my findings on correlations in an original thesis will inform academics and industry as to how best to choose and design systems for solving the problems that are important to them.

Intellectual Merit

As we engineer a greater variety of higher quality sensors for robots, the amount of data that needs to be correlated and filtered to a useful set of features for planning increases, in some cases exponentially with the number of sensors added. While many research efforts in robotics and computer science have worked towards finding the optimal algorithms for solving given tasks, tailoring computational hardware to a task is a relatively new area of scrutiny. Alternatives to my proposed approach include continued advances in sequential computer code optimization, parallelization and networking of sequential processors, neural networks, probability based processors, and ASIC design. In general, I think sequential processors will continue to advance, but when the datapath from sensor to planning module needs to be optimized for speed, I believe specialized circuitry will be more optimal in terms of development time and cost. I hope to provide insight into the ways researchers can leverage new commercially available technologies to improve data processing and control tasks. In a field motivated heavily by providing economical solutions to challenging tasks, choosing a computational platform that enables a feasible solution with fewer resources can lead to more time spent on core research. Selecting the correct hardware for a task can mean a savings in computation time, energy expenditure, and weight, which can ultimately enable researchers interested in other problems to produce better results in less time.

Broader Impacts

In the long term, I hope that my research will inform both academia and industry to make more capable robots using fewer resources and for lower cost. My research could easily be adapted from perception to the inverse problem of feedback control on highly articulated robots, where commands from a planner must be translated into hundreds of actuator commands. I plan to make the results of my research applicable and convenient for other researchers to integrate into their work by developing a software toolset to analyze their systems and suggest improvements by using alternative processor architectures, and offering guidance by hosting conference workshops on the subject. I also hope that as the cost of robotic technology goes down, more and more pre-college curricula can incorporate robotics into technology education. To me robotics is one of the most diverse ways to incorporate and apply concepts from science and engineering, and I want to help make it available to as many people as possible. Because this proposed research aims to improve the speed and implementation time of any application with real-time constraints on high-bandwidth parallel data, there are also many potential applications in other fields. As researchers are already exploring[4], analyzing protein folding could see a marked reduction in computation time exploiting parallelized hardware. Any research that currently resorts to supercomputers for performance improvements could potentially benefit from the insight my proposed research would provide.

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