Research Statement

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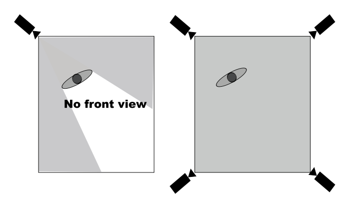
The robotics revolution is here. A world where teams of robots form a pervasive network of sensors, computers, and smart devices is not far off. By forming the "physical" layer of this network, robots will act as sensing and actuation agents for end-users. Robots will be able to collect and relay real-time data from hard to reach places at unprecedented spatio-temporal scales. Access to such data can enable new discoveries and help solve grand challenges in areas such as agronomy, oceanography, climate science, surveillance, and emergency response. Technology today has matured to the point where robots capable of autonomous operation in the air, on the ground, and in waters are available commercially. This trend will continue as the price-to-performance ratio of sensing, processing, and communication continues to fall. However, for such networks to be effective, they must be able to close the loop. In other words, we must develop efficient decision-making algorithms that make full use of the technology and ultimately further our understanding about the limits of technology and autonomy.

My research focuses on solving fundamental problems on deployment, coverage and path planning for robotic sensing. I develop algorithms that have rigorous theoretical performance guarantees and are extensively validated in the field. Most of these problems are NP-hard. However, exploiting the underlying geometric and combinatorial structure of these problems allows us to design efficient approximation algorithms. My research is motivated by applications where robots act as autonomous information gathering agents. I am equally interested in building robotic systems and studying practical issues that crop up in such applications.

Research Contributions

A connected world of robots and sensors will allow autonomous data collection across vast spatial and temporal scales while still providing fine-scale variability. My research has contributed towards this vision along three directions: *(i) How to cover large, complex environments using a minimum number of sensors and robots? (ii) How to optimize the robots' motion to enable long term continuous operation? (iii) How to enable efficient coordination between teams of robots?* Along with theoretical contributions, I have also collaborated with leading precision agronomists and environmental scientists and built robotic sensing systems that have been successfully deployed in large-scale field experiments.

Coverage in Complex Environments *What is the minimum number of omnidirectional cameras required to see all points in an n-sided polygon?* This question, known as the Art Gallery Problem (AGP), has been a subject of study for more than three decades. Cameras are one of the most commonly used sensors and understanding the geometry of visibility is critical for enabling efficient coverage of complex environments.



The standard formulation of AGP does not consider self-occlusions and may not suffice to obtain frontal views of a person moving in the environment. Obtaining good views from all orientations is important for applications such as surveillance and video-conferencing. With this as motivation, we studied AGP by imposing a new constraint termed $\triangle$-guarding. The $\triangle$-guarding constraint [2] states that a point is covered if it lies in the convex hull of the cameras that are visible from the point. If all points are $\triangle$-guarded, then the perimeter of any convex object anywhere in the environment will always be visible, despite self-occlusions.

While we would expect to place more cameras with the additional $\triangle$-guarding constraint, it is not clear how many more cameras are needed. In [5], we showed that the numbers of cameras might increase drastically. Specifically, we proved that $\Omega(\sqrt{n})$ cameras are always necessary for $\triangle$-guarding any n-sided simple polygon. Since $\Omega(\sqrt{n})$ can be a prohibitively large number, we focused on guarding only regions of interest when the input is a set of chords (representing, for example, straight paths a person may take) and the goal is to $\triangle$-guard at least one point per chord. We presented a constant factor approximation algorithm, one of the few such guarantees for visibility-based coverage problems. This work was presented at ICRA [5] and a journal version is under review at Elsevier Computational Geometry: Theory and Applications.

At Penn, I am studying the mobile version of AGP. In a recent submission [9], we showed how to design paths for a robot team to collectively see every point in an environment in the least time. Although this generalizes the already challenging AGP, we presented a 4-approximation algorithm for the special class of street polygons.

Long Term Autonomy A major bottleneck for practical deployments is the limited on-board battery capacity of the robots. We must develop solutions at multiple levels in order to address this energy challenge. In [8], we derived minimum energy paths and velocity profiles using optimal control for mobile robots with car-like steering. In [1] we demonstrated how Gaussian Process regression can be used to build a map of solar energy, using only current measurements from the solar panel and with no prior knowledge of the environment. Beyond optimizing at an individual level, robots should collaborate with each other and overcome their energy restrictions. For example, small aerial robots with severe energy limitations can use larger ground robots as carrier vehicles and extend their operating range. In [10], we demonstrated the *symbiotic* behavior of aerial robots that can transport themselves to far away locations at the small energy expense of taking-off and landing on the ground robots. Specifically, we demonstrated how to model this symbiotic behavior in the form of a metric graph which allows us to apply a known approximation algorithm for the *orienteering* problem. Our algorithm plans the paths for an aerial and ground robot so as to maximize the number of points visited by the aerial robot within its energy budget.

Cooperation for Multi-Robot Systems Consider the problem of tracking a collection of moving targets with a team of robots. This is an important task with many applications such as wildlife tracking, crowd surveillance, and aerial photography. Aerial robots can potentially track more targets by flying to higher altitudes. However, this may reduce the quality of the tracking since the images are taken from further away. Thus, there is a trade-off between the number of targets tracked and the quality of tracking. In [7], we showed that $k \geq 3$ robots may not be able to track $n > k$ targets while maintaining an approximation guarantee on the quality of tracking at all times. In light of this result, we studied the problem of how to assign robot trajectories in order to maximize the number of targets tracked or maximize the quality of tracking. We proved that a simple algorithm that greedily chooses trajectories yields a 1/2 approximation. This work was a collaboration with Antonio Franchi (Max Planck Institute) and I supervised one of his student during the experimental evaluation.

Inter-robot communication plays a crucial role in multi-robot coordination. There are two typical approaches to handling connectivity: imposing connectivity as a constraint, or ignoring connectivity and relying on opportunistic communication when robots rendezvous. However, both approaches are far from optimal. Instead, a desirable solution is one that plans when and where the robots rendezvous and coordinate. In [11], we studied how to actively localize a stationary target using robots with limited communication range. Our formulation penalizes the time it takes to to travel to both, measurement and rendezvous locations. We presented optimal and approximation algorithms for this problem and validated their performance through field experiments.

Systems for Robotic Sensing Applications

While the vision of a pervasive internet of robots may seem distant, there are immediate applications where robotic sensing systems can make a big impact. These applications, in turn, motivate new research problems and act as excellent proving grounds for robotics systems.

Precision Agriculture Precision agriculture is a data-driven technique to estimate and predict the health of crops which is then used to design targeted fertilizer treatment plans. Precise management of farm inputs can lead to tremendous cost savings and environmental benefits. Sensing is a critical aspect of precision agriculture.

In [10], we presented the design of a robotic sensing system, in collaboration with leading precision agriculture researchers at Minnesota. Our proposed system combines soil measurements from ground robots with multi-spectral images obtained from aerial robots to precisely estimate nitrogen deficiency in crops. We demonstrated how to classify a field into regions with different nitrogen levels using Gaussian Process regression. Additional measurements must be obtained at points that are potentially misclassified. Obtaining soil measurements can be a time-consuming process. Finding a tour that obtains all measurements in the least amount of time requires solving a general version of an already challenging problem, namely the Traveling Salesperson Problem with Neighborhoods (TSPN), with additional practical constraints. Nevertheless, we presented a constant factor approximation algorithm for this problem under practical assumptions.

Robots promise to play a big role in the next generation of farming. I am excited to contribute towards this role. With other leaders from U.S.A. and Australia, I am organizing a workshop that will bring together roboticists and agronomists at ICRA '15. At Penn, I am helping write a grant proposal (that will be submitted to USDA via the National Robotics Initiative) on using teams of aerial robots as co-scouts for farmers.

Environmental Monitoring Robotic sensors can gather high resolution data at vast spatio-temporal scales—capabilities that are invaluable for scientists tackling critical environmental issues. Consequently, it is important to develop efficient algorithms and systems for robotic environmental monitoring.

At Minnesota, I was part of the team building a robotic system to autonomously monitor Common Carp, an invasive fish species. We collaborated with biologists who are studying the behavior of these fish. Our system [3, 4] employs radio antennas carried by robotic boats in the summer and wheeled robots operating on frozen lakes in the winter. We introduced a new coverage problem motivated by the scenario that fish biologists can often specify regions that are likely to contain fish. We presented a constant-factor approximation for the problem (that generalizes TSPN) of finding a tour that covers all regions in minimum time. I have also worked on information gathering algorithms to precisely localize the fish after having found them [12]. This system has been successfully deployed several times in multiple lakes over the past four years.

Future Research Directions

My long term goal is to contribute solutions that will help create a pervasive network of sensors, robots, and smart devices. Towards this end, in the near term, my research will have three main thrusts.

Cooperation for Heterogeneous Robot Teams As robotic technology matures, we will increasingly see autonomous systems cooperate and collaborate with humans. For example, driver-less cars will have to cooperate and share resources with manually driven cars. The next generation agriculture solutions will have robot teams collaborating with human scouts and augmenting the scouts' expertise with precise data gathering. A primary challenge will be to develop new planning algorithms that exploit the synergy between humans and robots. These algorithms must take into account the uncertainty associated with human actions while at the same time providing strong guarantees on the safety and performance of the robots. I am also interested in designing algorithms for robots that collaborate not only by sharing information but also by physically assisting each other. For example, how can a team of energy-limited aerial robots quickly monitor an environment (or deliver mail) along with the help of mobile recharging robots (or manually driven delivery vans)? How can robots with vastly different speeds, agility, and reliability collaborate to complete tasks with performance guarantees?

Coverage in Practical Environments Many of the worst-case bounds for coverage problems are based on creating pathologically bad environments. There have been attempts to define more realistic environments, e.g., *fat* polygons. Nevertheless, several problems, including the existence of constant-factor approximations, remain open. The effect of uncertainty and noise on visibility has largely not been studied. In [6], we studied the placement problem considering measurement noise but ignoring visibility and environment constraints. However, designing placement schemes that are robust to uncertainties in the environment representation and inaccuracies in placing cameras remain important open problems that I will work on.

Long Term Operation for Complex Missions Most sensing problems are typically formulated as optimization problems in one variable (e.g., time, energy, quality, connectivity) with other variables either imposed as constraints or ignored. While this is appropriate for short deployments (order of hours), the situation will be more complicated as we move towards the vision of a pervasive network of robots and sensors (order of months). The objectives for the robots may change over time. For instance, there may be times when harvesting energy is more important whereas at other times collecting high quality data may be critical. For missions where the specifications change from time to time can we determine *a priori* the optimal size and composition of robot teams? A principled study that characterizes and quantifies the trade-offs between various components of the system is needed. I plan to carry out research that can address such questions and eliminate guesswork when it comes to deploying robotic systems for long endurance missions.

These are exciting times for robotics, as evident from the recently created National Robotics Initiative and renewed interest from the industry. We can look forward to a connected world where robots will work alongside agronomists, biologists, and first responders, and perform tasks deemed too complex, unsafe, or infeasible today. As I have done in my research so far, I will develop algorithms and build systems to solve fundamental robotics problems that can ultimately help solve grand challenges of our day.

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