The bulk of my research will focus on foraging theory and its applications in engineering. Behavioral ecologists use foraging theory to model and analyze animals' strategies for investing resources to find and process food. A popular guide to foraging theory is the 1986 book, *Foraging Theory*, by D. Stephens and J. Krebs, or the more recent 1999 book, *Models of Adaptive Behavior: An approach based on state*, by A. I. Houston and J. M. McNamara. In *Foraging Theory*, Stephens and Krebs use a well-known model of the expected rate of caloric "point" gain that a predator will receive given the assumption of Poisson distributed prey arrival times. Using this model, known as *Holling's Disc Equation*, Stephens and Krebs are able to give algorithms predicting the optimal behavior of a predator.

In principle, the optimal conditions that Stephens and Krebs predict could be used for control of an automatic agent facing tasks which have a certain point value. For example, Stephens and Krebs give a "prey algorithm" that predicts which prey should be processed when encountered and which prey should be ignored. This algorithm should then also be able to predict which targets an unmanned aerial vehicle (UAV) should take the time to process and which targets the UAV should ignore completely. However, there are some problems with the derivation of the these algorithms that do not make them directly applicable to engineering. One major problem is that stochastic and deterministic methods have been improperly mixed in the derivations of these algorithms. On top of this, even assuming validity of the algorithms, Stephens and Krebs place strong restrictions on environmental parameters that prevent the application of many of the algorithms to the general class of engineering problems.

Thus, it is the goal of my research with Professor Kevin Passino to develop a proper stochastic model for rate of point gain and to show proofs of the optimality conditions on this new model that make no assumptions about the environmental parameters. In particular, the prey algorithm, which chooses which prey types to process and which prey types to ignore, and the patch algorithm, which chooses when to leave an area of diminishing returns, will be constructed for the optimal case for arbitrary environmental parameters. Moreover, we are going to evaluate the potential to derive vehicle control polices by optimizing performance metrics appropriate for UAV applications.

This will have completed and extended the work of Stephens and Krebs to a much more general case. However, there are a number of questions not even addressed by Stephens and Krebs that will have a significant impact on engineering design. One question of interest to me is the one posed by R. Gendron and J. Staddon in their 1983 *American Naturalist* paper, "Searching for cryptic prey: The effect of search rate." In this paper, Gendron and Staddon use the same *Holling's Disc Equation* to show that there exists an optimal non-maximal prey search rate in the presence of prey that camouflage themselves and thus require more time for detection. The choice of search rate is important for engineering due to sensor sensitivity to speed. For example, low bandwidth sensors will be ineffective at high speeds, so the agent's optimal speed will most likely not be the maximum speed of the agent but some lesser speed where the sensors can operate properly. However, the Gendron and Staddon paper is only meant to explain an apparent speed modulation in observed predators in nature; it does not propose a general framework for predicting what an optimal speed might be in a given environment. This is an important question that I will answer in the course of my research.

Next, neither Stephens and Krebs nor Gendron and Staddon have a satisfactory theoretical treatment of how an animal copes with imperfect information. In many engineering cases, the agent will not know the expected arrival rate of its tasks a priori and will have to estimate this "on the fly." If the agent is additionally modulating its speed with changes in perceived arrival rate, those changes in speed will naturally cause more changes in the perceived arrival rate. Thus there is a circular relationship that gives the trajectory of the agent's speed dynamics that need to be well-understood.

It is worth noting that while the UAV case may be an obvious application of this research, it is not the only application into which this research will provide insights. Servers servicing networks that bring in tasks can be thought of in terms of foragers. Even personal computers processing local tasks can be thought of as foragers. In fact, in the interesting case of a personal computer that does useful processing in its idle time, the computer may act like a forager that actually gains points when searching. This is an interesting case that could not be handled with the assumptions currently held by Stephens and Krebs since they assume that a forager always suffers a cost for searching. In the case where searching brings some positive gain, then the optimal choice of prey may be to ignore all tasks if no combination of tasks achieves the same point gain as the idler task.

Foraging theory also applies to the social case, where multiple foragers sharing one space may interact. In "social foraging theory," best summarized in the book, *Social Foraging Theory*, by L. Giraldeau and T. Caraco, evolutionary game theory is used to analyze the optimal "designs" created by evolution. Understanding the dynamics of social agents will undoubtedly give tremendous insight on optimal control schemes for decentralized controllers for engineering applications. I am particularly interested in the theoretical requirements for emergent cooperation between agents and how to design an optimal mix of heterogenous agents to accomplish a task. Our current plan is to apply the theory to the design of optimal robust cooperation for a group of UAV's performing cooperative search for targets.

These questions surrounding foraging theory will account for the bulk of my research during my fellowship tenure. Each of the major issues here will be the subject of a journal paper. The goal is to publish the full details of the topics mentioned here in a book expected to be titled, *Foraging Theory for Engineering*, authored by engineering Professor Kevin Passino, biology Professor Tom Waite, engineering graduate student Burt Andrews, and myself. We currently have more than 80 pages written for this book.

My interest in these topics was recreational at first. The sources of my interest were a number of books that I read outside of school which discussed complex biological systems. As I began to understand some of the origins behind the emergent structures and behaviors of these systems, it became clear to me that understanding their dynamics would be extremely useful to future work in engineering. Controls engineering is being pushed into the multi-agent arena that is preferably decentralized. Before building these systems, it will be extremely useful to understand already built working examples of similar systems that we already find in biology. Additionally, I find it immensely appealing that applying engineering methodology to the analysis of biological systems may one day provide some sort of new insights to practicing biologists. If biology can assist engineering, engineering should be able to assist biology, and being a part of that would be extremely rewarding to me.

Now, in order to make sure I have the appropriate background to study biology in this way, I am taking a number of biology and ecology courses while pursuing my graduate degree. In order to understand some of the more complex dynamics in these systems, I am taking a number of fairly advanced mathematics courses. Together with my engineering background, I feel that I will be adequately equipped to be productive in a field that is very interesting to me.