RESEARCH STATEMENT

Mahni Shayganfar (mshayganfar@wpi.edu)

My current research span the areas of computational collaboration theories, affective computing, human-robot collaboraiton, and cognitive robotics. A common thread in my research is in developing a theory (Affective Motivational Collaboration Theory), design of a domain-independent architecture, and the framework which uses this architecture to provide a collabortive behavior for robots or vritual agents. I have resorted to prominent computational collaboration theories, i.e., SharedPlans theory, and computaitonal models of emotions, i.e., cognitive appraisal theory to develop my own theory. Broadly speaking, my research belongs to the area of human-robot collaboration and its underlyign processes, a growing field which has influence in different leading industries such as autonomous vehicles, space exploration, manufacturing, and any situation requiring human-robot teamwork.

Background

The construction of robots that are intelligent, collaborative problem-solving partners is important in robotics and applications of Artificial Intelligence. It has always been important for us to make robots better at helping us to do whatever they are designed for. To build collaborative robots, we need to identify the capabilities that must be added to them so that they can work with us or other agents. As Grosz says, collaboration must be designed into systems from the start; it cannot be patched on [7]. Collaboration is a special type of coordinated activity in which the participants work together performing a task or carrying out the activities needed to satisfy a shared goal [10].

Collaboration involves several key properties both in structural and functional levels. For instance, most collaborative situations involve participants who have different beliefs and capabilities; most of the time collaborators only have partial knowledge of the process of accomplishing the collaborative activities; collaborative plans are more than the sum of individual plans; collaborators are required to maintain mutual beliefs about their shared goal throughout the collaboration; they need to be able to communicate with others effectively; they need to commit to the group activities and to their role in it; collaborators need to commit to the success of others; they need to reconcile between commitments to the existing collaboration and their other activities; and they need to interpret others' actions and utterances in the collaboration context [8]. These collaboration properties are captured by the existing computational collaboration theories.

As I mentioned, to be collaborative, partners, e.g., a robot and a human, need to meet the specifications stipulated by collaboration theories. These theories argue for an essential distinction between a collaboration and a simple interaction or even a coordination in terms of commitments [6, 14]. The prominent collaboration theories are mostly based on plans and joint intentions [2, 11, 13], and they were derived from the BDI paradigm developed by Bratman [1] which is fundamentally reliant on folk psychology [15]. The two theories, Joint Intentions [2] and SharedPlans [11], have been extensively used to examine and describe teamwork and collaboration.

SharedPlans theory - The SharedPlans model of collaborative action, presented by Grosz and Sidner [9, 10, 11], aims to provide the theoretical foundations needed for building collaborative robots/agents [7]. SharedPlans is a general theory of collaborative planning that requires no notion of joint intentions, accommodates multi-level action decomposition hierarchies and allows the process of expanding and elaborating partial plans into full plans. SharedPlans theory explains how a group of agents can incrementally form and execute a shared plan that then guides and coordinates their activity towards the accomplishment of a shared goal. SharedPlans is rooted in the observation that collaborative plans are not simply a collection of individual plans, but rather a tight interleaving of mutual beliefs and intentions of different team members.

Joint Intentions theory - Following Bratman's guidelines, Cohen and Levesque propose a formal approach to building artificial collaborative agents. The Joint Intentions theory of Cohen and Levesque [2, 3, 4, 5, 12] represents one of the first attempts to establish a formal theory of collaboration, and due to its clarity and expression, is a widely used teamwork theory. The basic idea of Joint Intentions theory is based on individual and joint intentions (as well as commitments) to act as a team member. Their notion of joint intention is viewed not only as a persistent commitment of the team to a shared goal, but also implies a commitment on part of all its members to a mutual belief about the state of the goal. In other words, Joint Intentions theory describes how a team of agents can jointly act together by sharing mental states about their actions while an intention is viewed as a commitment to perform an action. A joint intention is a shared commitment to perform an action while in a group mental state [3].

STEAM - Tambe in [16] argues that teamwork in complex, dynamic, multi-agent domains requires the agents to obtain flexibility and reusability by using integrated capabilities. Tambe created STEAM (simply, a **S**hell **TEAM**work) based on this idea. STEAM's operationalization in complex, real-world domains is the key in its development to addressing important teamwork issues. STEAM is founded on the Joint Intentions theory and it uses joint intentions as the basic building block of teamwork while it is informed by key concepts from SharedPlans theory.

I believe the SharedPlans and Joint Intentions collaboration theories are the most well-defined and well-established theories in computer science. I found SharedPlans theory more convincing than the other major and subordinate approaches, with respect to its inclusive explanation of the collaboration structure and its association to discourse analysis which directly improves the communicative aspects of a collaboration theory. I also understand the value of Joint Intentions theory due to its clarity and closeness to the foundations of collaboration concepts. These specifications of the Joint Intentions theory can make it applicable in multi-agent system designs and human-robot collaboration. I also consider hybrid approaches valuable, such as STEAM, if they clearly understand drawbacks with existing theories and successfully achieve better collaborative agents by infusing different concepts from different theories.

In my Ph.D thesis, I attempt to lay a computational framework for the theory I have developed based on SharedPlans and Cognitive Appraisal theories. A great deal of my work has benefited from the integration of these well-established theories and their underlying structure.

2. Limitations (funnel into my thesis)

Although all these theories are well-defined and properly introduce collaboration concepts, they mostly explain the structure of a collaboration and they lack the underlying domain-independent processes with which collaborative procedures could be defined more systematically and effectively in different applications.

3. Introduce topic and research question

4. Synopsis of first part of my work

5. Synopsis of second part of my work

6. Overview of human study at the end

7. Verification method

8. Say how current research can apply to their research

9. Exaplain why the research is valuable

An Analytical Framework to Analyze Router Architectures

In the past decade, router design has enjoyed both widespread academic interest and commercial success. I ask the following question — *Is there a common technique, which allows us to analyze router architectures that give deterministic guarantees?* I observed the existence of such a technique called constraint sets, in the course of solving two open problems about scaling router capacity —

1. *Is it possible to emulate a fast ideal router, using only slower speed routers?*
2. *Is it possible to emulate an ideal centralized shared memory router using only distributed memories?*

Constraint sets are a generalization of the Pigeon-hole principle applied to routers. I showed that router design can be considered as a game where arriving pigeons (packets) are load balanced amongst pigeon-holes (memories). It is surprising that the above problems can be solved [**?**, **?**, **?**] in a simple manner using the Pigeon-hole principle because they refute many commonly accepted myths about router design. Also the method of analysis is eye-opening because it captures the structural requirements of any router. I came up with a generic model for a class of routers called Single Buffered Routers. I showed how the Pigeon-hole principle can be applied in the analysis of Single Buffered Routers that give deterministic guarantees. Later, I extended the analysis to routers with two stages of buffering [**?**]. Thus our model and analysis technique presently incorporates almost all the router architectures in use in the core of the Internet today and shows how router capacity can be scaled in an efficient manner.

Deterministic Architectures for Packet Processing

All network equipment perform packet processing. However it is still not well understood, primarily due to the variety of different processing tasks.

These tasks place a heavy demand on instruction and memory bandwidth, which prevents them from being implemented on general-purpose network processors. While specific solutions exist, in most cases it is not known whether they are optimal, whether they are complete i.e. support all necessary packet processing features and whether they give any performance guarantees. I look at three different aspects of this problem —

1. *Optimal and flexible packet buffers, which eliminate cache misses*

   Packet buffers are built using cache hierarchies. As is well known, caching can only give statistical guarantees on packet access time, resulting in unpredictable packet latency. In contrast, I proposed deterministic algorithms, which exploit the characteristics of memory requirements for networking to design a memory hierarchy, which eliminates cache misses. I showed how the optimal buffer caching algorithm can be modeled using difference equations and used adversarial traffic patterns to show that it is optimal [**?**]. This resulting memory architecture supports the high access speeds of the cache while having the large storage capacity of main memory, obviating the need for any special purpose memory for networking. Later, I showed how the cache hierarchy could be designed to allow flexibility in choosing any buffer access latency. A number of router companies such as Cisco, Juniper as well as main memory manufacturers like Infineon, Rambus and Micron have shown interest in this technique.

2. *Optimal and deterministic architectures for statistics and state maintenance*

   I (along with a colleague) showed using potential functions how there is a direct relation between the optimal architectures for buffering and maintaining statistics counters [**?**]. Similarly I showed analytically how an algorithm, which gives deterministic delay bounds could be designed for maintaining connection state.

3. *A complete and flexible architecture for packet classification*

   Packet classification requirements vary widely. For example, firewalls need classification on packet headers, while an intrusion detection device requires classification of the packet content. Previous research has focused on being able to classify at very high rates. In contrast, I (along with a number of colleagues) focused on developing a classifier, which is flexible and complete i.e. it could be programmed to perform a number of classification tasks and give deterministic performance guarantees. As a first step, we identified the elementary building blocks for packet classification in terms of an abstract language. We then designed a parallel hardware architecture to implement this language. This resulted in a commercial implementation of a chip set (presently marketed by PMC-Sierra) called ClassiPI [**?**]. Among others, the ClassiPI chip set is currently in use in Cisco's Content Services Switches.

Distributed and Greedy Algorithms for Packet Switching

Switching theory is replete with the analysis of optimal algorithms, which can give ideal performance, but have large complexity. What are of interest are practical algorithms that can be easily implemented. I answer the following open questions, which throw light on two classes of practical algorithms.

1. *Is there a distributed switching algorithm, which gives performance guarantees?*

   The crossbar is the most common switching fabric in the core of the Internet. However, the known switching algorithms required to give deterministic performance guarantees are centralized and hence have a high communication overhead. I (along with a colleague) analyzed the feasibility of distributed algorithms for a modification of the crossbar fabric called the buffered crossbar. We derive analytically using combinatorial arguments and counting techniques the conditions under which a suite of distributed algorithms can give both statistical and deterministic guarantees respectively. Since our algorithms need only local state, do not require communication with each other, and can operate independently on each input and output port, they are readily implementable. Our results show that Internet routers built using crossbars, such as Cisco routers, can be upgraded in a practical manner using our distributed algorithms on buffered crossbars and give ideal performance [**?**].

2. *When can greedy algorithms give optimal switching performance?*

   Contrary to intuition, it is known in queueing theory that a greedy switching algorithm such as the maximum size matching which maximizes the instantaneous throughput of the switch may not maximize the long-term switch throughput. Hence, greedy algorithms are not in use in practice. However greedy algorithms are of practical interest due to their low implementation complexity. I show using Lyapunov functions the conditions under which such algorithms give 100% throughput [**?**].

Network Architecture — A Research Agenda

In the course of my research, I have noticed that the overhead (in terms of size, power and cost) of designing networking components, which give performance guarantees is small. This is mainly due to two reasons. First, the inherent nature of networking makes many of these problems tractable. Second, a number of hardware advances in Architecture, insights in Algorithms *&* Combinatorics, as well as analysis techniques from Probability, *&* Queueing Theory aid in the design of elegant and simple solutions. I envisage the field of *Network Architecture* created from the ground up, building upon the foundations of a number of fields including those mentioned above.

In the near future, I am interested in the principles involved in the design of basic networking components. These include hardware components (e.g. scalable memories, network processor and co-processor architectures) and software techniques (e.g. network algorithms, packet processing techniques). Simultaneously, I intend to understand how large components, which use the above building blocks can be architected. My research will focus on how these basic and large components can be built in a scalable manner while maintaining performance guarantees. In particular, examples of large components that I have a keen interest in are switches (e.g. packet and circuit switches, multi-service routers etc.), security devices (e.g. firewalls and intrusion detection systems), network maintenance devices (e.g. measurement, management infrastructure) and application aware devices (e.g. web server load balancers, proxies) etc.

In the future, though performance and scalability will remain key, I also intend to look at issues such as *fault tolerance, graceful degradation, reliability and uptime* of networking systems, which will become more relevant. I also believe that as systems become increasingly large and inter-dependent, *simplicity in design and component re-use* will be major factors. Parallelism can play a key role here.

Indeed, many of our proposed solutions, involve component re-use and parallelism, which can aid and abet the above.

My research will involve a good mix of futuristic and present day research. One part of my work will focus on fundamentally different proposals and radical solutions. As an example — can we finally achieve real-time streaming over the Internet, assuming that the various network components give performance guarantees? In contrast, I intend to devote the other part of my work on practical systems, which have immediate relevance and impact in Industry. I intend to work closely with a number of researchers in related fields. Similarly, I intend to collaborate with Industry in understanding and developing solutions for practical problems. I believe my past experience of research work done jointly with a number of colleagues as well as my prior record of participation with Industry will help me achieve this. I am excited at the prospect of learning, contributing, giving shape and making an impact in this upcoming and challenging field.

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