TEXAS RESEARCH ALLIANCE

THE UNIVERSITY OF TEXAS AT DALLAS

SMART CITY TRANSPORTATION SYSTEM FINAL RESEARCH REPORT – OCTOBER 31ST, 2016

OVERVIEW

From 10/01/15 to 9/31/2016, Professors Nicholas Gans and Rym Zalila-Wenkstern lead a collaborative project to lay the ground work for systems that will increase the quality and efficiency of travel times by implementing adaptive algorithms in traffic control systems. The multidisciplinary team simulated the West End section downtown Dallas, TX and tested methods to optimize traffic flow. The simulation involved novel real-time, current condition-based optimization algorithms running on state-of-the-art, agent-based software to provide live updates to traffic lights. Based on based on the research findings of this project, one research paper was accepted for publication in the proceedings of the IEEE Conference on Decision and Control, one paper was submitted to the American Controls Conference, and one is in the process of being submitted to the International Conference on Autonomous Agents and Multi-Agent Systems.

INTRODUCTION

The impact of traffic congestion on commuters' time is well known, with US residents spending an average of 111 hours annually in gridlock. A recent study indicates that in addition to the negative impact on drivers and the environment, traffic congestion robs US households of $1,700 and the US economy of $124 billion, annually. Part of the solution for these problems is in optimal timing for traffic signals to reduce the traffic congestion at the intersections. A report from United States Environmental Protection Agency estimates the cost for updating timing plans would be around $16,400 per signal. This cost would be offset by economic gains, but lights would likely have to be regularly retimed. Due to the heavy expense incurred in retiming these signals and the budget constraints involved, a manual retiming is done typically only every three years.

In addition to the costs of retiming, the drawback of a fixed-time strategy is that it does not consider real-time measurements. Systems have been developed that can incorporate real-time measurements, but they typically rely on simplified traffic models. This limits their capabilities to just a few intersections, and their performance has been called into question. Over the past year we completed an initial investigation of using a distributed, model-free, real-time optimization algorithm for finding the optimum traffic light timings at multiple intersections. We show the effectiveness of the algorithm in a large scale simulation software known as Multi-Agent based Traffic Safety Simulation systEm (MATISSE). In particular, MATISSE models each traffic entities like vehicles and traffic lights as agents, which can pass information to each other.

The most striking feature of MATISSE is its ability to simulate thousands of vehicles, each having a randomized behavior.

PERSONNEL

Dr. Nicholas Gans was PI of this one-year project, and Dr. Rym Zalila-Wenkstern was Co-PI. Two UT Dallas students (Saurav Kumar and Behnam Torabi) and one post-doc (Dr. Mohammad Al Zinati) were supported by the grant. Saurav Kumar is a PhD student in Electrical Engineering working under the supervision of Dr. Gans. Behnam Torabi is a Ph.D. student in Software Engineering working under the supervision of Dr. Zalila-Wenkstern. Dr. Mohammad Al Zinati is a former Ph.D. student of Dr. Zalila-Wenkstern and is currently an Assistant Professor at Jordan University of Science and Technology.

TASK 1 –MULTI-OBJECTIVE EXTREMUM SEEKING CONTROL FOR MODEL-FREE REAL TIME OPTIMIZATION

Motivation

Traffic networks are incredibly complicated, and developing reliable models remains a challenge. Modern attempts to optimize traffic have generally relied on simple models for traffic flow over a few traffic lights in a corridor. Model-free optimization is an attractive option, which can attempt to optimize costs without ever needing or knowing a model, simply by monitoring the change of costs as variables are changed. In the case of traffic network, costs could be the number of cars stopped at all lights over time and input variables could be timing properties of traffic lights. Such approaches have been little explored in the context of traffic lights, and are often slow to converge, which could make them incompatible with traffic control. Furthermore, we must balance multiple objectives that might be in conflict, such as optimizing traffic in multiple directions. We propose to investigate the use of Multi-Objective Optimization (MOO) to satisfy multiple optimization tasks.

Approach

We first explored methods of Extremum Seeking Control (ESC). ESC has been extensively used in solving single objective optimization problems. However, there are few contributions towards implementing ESC in a multi-objective setting. A few attempts at using ESC in MOO have not followed a typical MOO framework and are highly specialized for specific problems. We designed a novel a novel algorithm to achieve Multiple Gradient Descent using ESC, which had not been previously demonstrated. A key insight was the use of multiple ESC loops to estimate the gradient for each objective with respect to each input variable, and a higher level ESC loop to find the path that best optimized all gradients. This is illustrated in Figure 1.

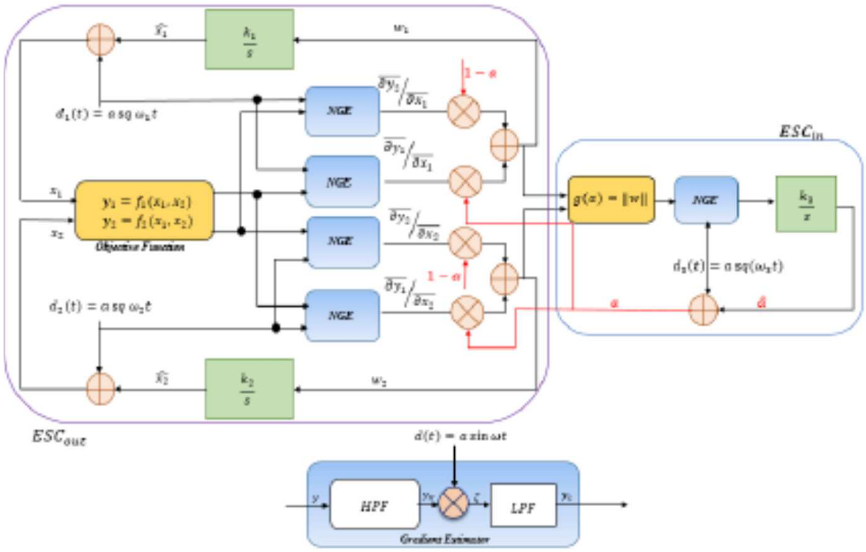


Figure 1-Block diagram of MOO using ESC

The approach works very well. Starting from any initial condition, the controller converge to a set of input variable that optimize all objectives in a balanced manner. This is seen in a simulation result in Figure 2. The system had two input variables x1 and x2. We were attempting to optimize two objective functions with individual maximums at [x1, x2]= [-5,-10] and [x1, x2]= [2,-2]. Note that these two functions are in contention, but any point between the two maximums is a balanced optimization solution. Starting from any initial values for x1 and x2, the ESC MOO system guides the variables to such a balance solution along a fairly straight trajectory. This work was accepted to the 2016 IEEE Conference on Decision and Control, and will be presented in December. Future will focus on theoretical proof of convergence and implementation with real-world problems.

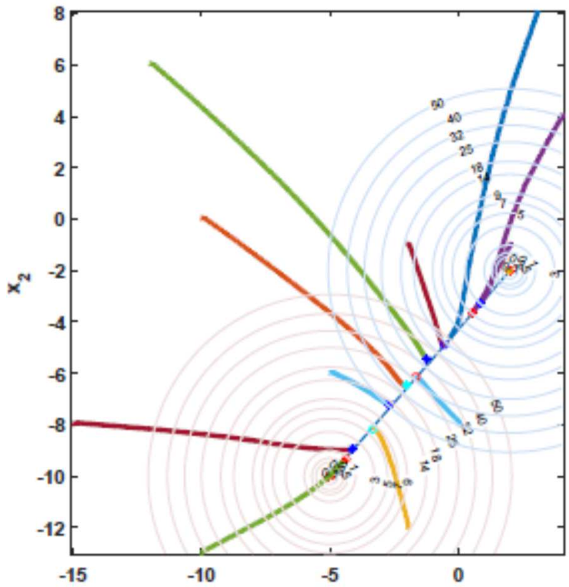
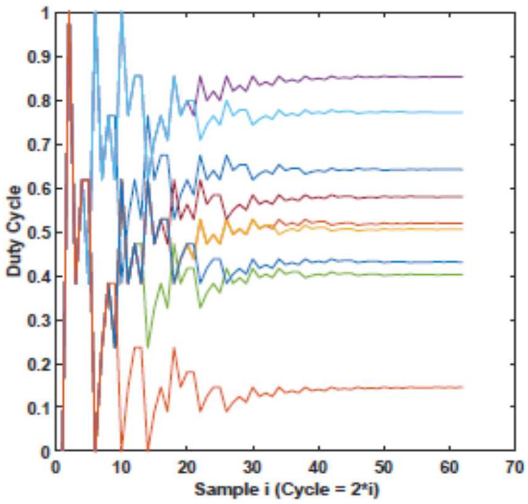


Figure 2- Convergence to different balanced solutions starting from different initial conditions

This theoretical work was promising. We next turned our attention to the problem at hand of optimizing traffic signals timing. We focused on optimizing traffic conditions that can be readily measured by the sensor technologies commonly in place at existing intersections. We employed a model of the West End section of downtown Dallas which features accurate distances between all intersections. We adapted our ESC results to a Golden Section Search optimization on four critical intersections, tuning the timing of green and red lights in each direction to minimize the running tally of stopped cars over a time window. Monte Carlo analysis was performed to account for the randomness of vehicle's behavior, which showed an improvement of 5% in the average number of vehicles stopped at the intersections over the pre-timed traffic systems. This improvement is on par with what is achieved by periodic retiming.

Results can be seen in Figure 3. The left graph shows the convergence of the green light timing of a particular intersection in the map to different optimal values for 9 simulation runs. Since traffic is initialized differently each simulation, the light timing converges to difference values each time. This shows the adaptability of the approach. It is also worth noting that convergence is at the same rate every run. The right side of Figure 3 shows converge of the signal timing for four lights during a signal run. We can see that all four lights also converge at the same rate of about 30 cycles. 30 cycles for converges would be about 1 hour. That is 16x faster than the only other model-free traffic signal optimization work we are familiar with. One hour may still be too slow to be practical, and attempts to speed it up will be addressed in future work. Other future work will be to increase the number of input variables and output metrics optimized.



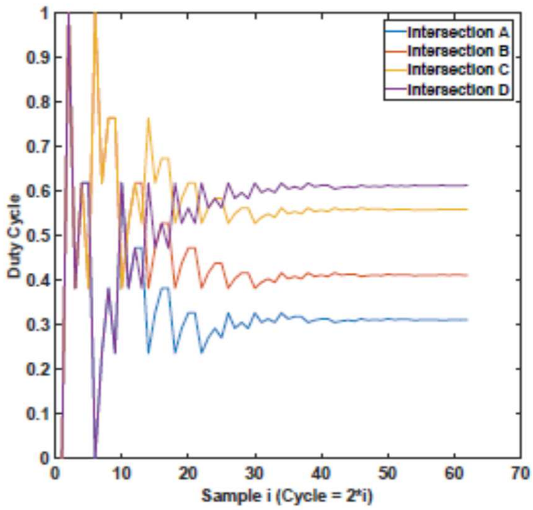


Figure 3-(left) Convergence of duty cycle for multiple simulation runs for the same intersections. (right) Convergence of duty cycle using GSS for multiple intersections for one run.

TASK 2 – SIMULATION OF TRAFFIC ENVIRONMENTS

The algorithms discussed above were implemented in MATISSE, a large-scale multi-agent based platform for the simulation of traffic systems, developed at the Multi-Agent and Visualization systems (MAVs) lab at UT Dallas. In order to simulate real-world traffic-networks (including the West-End section of downtown Dallas), several existing features of MATISSE needed to be improved and new features added. We completed the following tasks.

1. **Imported Real-World Maps in MATISSE**
   MATISSE was used to test agent-based traffic systems using traffic networks defined by the user of the simulation. In order to model real-world, complex traffic networks, one cannot rely on the manual specification of the road segments, lanes, lane directions, intersections, etc. Our goal was to automate the road network definition process by importing OpenStreeMap road network data directly into MATISSE. This task proved to be challenging for the following reasons.
   a. OpenStreetMap's data is incomplete (missing details such as number of lanes, intersection type, etc.). In order to address this limitation, *we developed algorithms which make use of traffic engineering standards to populate maps with the missing data*.
   b. OpenStreeMap's data is in the *osm* format which is incompatible with MATISSE's data format. *We developed a complex algorithm to automatically convert osm data into MATISSE's format*.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generator="CGImap 0.3.3 (31208 thorn-02.openstreetmap.org)" version="0.6">
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       <tag v="swimming_pool" k="leisure"/>
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          2014" k="source"/>
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</osm>
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Figure 3 - OpenStreetMap's osm format

2. **Optimized Imported Road Network Data to Increase Performance**
   The OpenStreeMap's *osm* files contain a large number of unnecessary nodes which consume processing power and decrease the performance of the simulation. *We developed advanced graph drawing algorithms to automatically optimize the graph structure* by removing unnecessary nodes and edges.

Figure 4 - (a) An intersection in OpenStreetMap (b) Same intersection in MATISSE

3. **Augmented MATISSE's Road Graph Structure**

   In MATISSE, the complex road graphs were defined on the assumption that only roads with the same number of lanes can be connected at intersections.

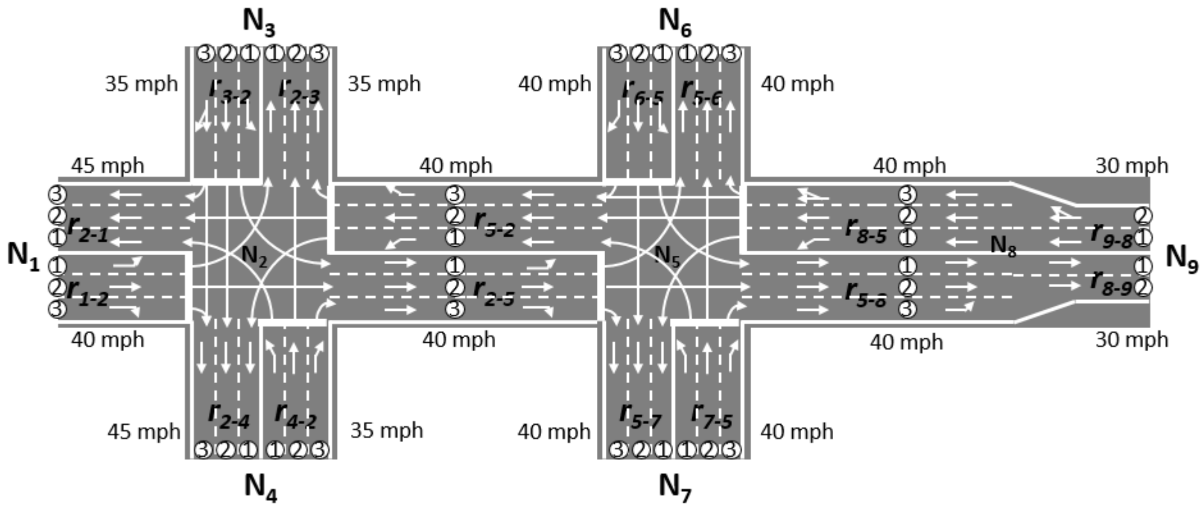

Figure 5 – MATISSE's Road Network Graph

This condition proved to be a limitation since in a real-world setting, roads with different numbers of lanes can be connected to each other at intersections.

Our effort required the *update of MATISSE's core graph structure*, and the *update of the graph traversal algorithms*.

4. **Integrated a new 2D Visualizer to MATISSE**
   The previous 2D visualizer was obsolete. We replaced it with ArcGIS, a powerful visualization engine for GIS applications. This change required the *development of a new algorithm that reads the MATISSE graph information and converts it to polygons and polylines* that can be effectively drawn by ArcGIS.

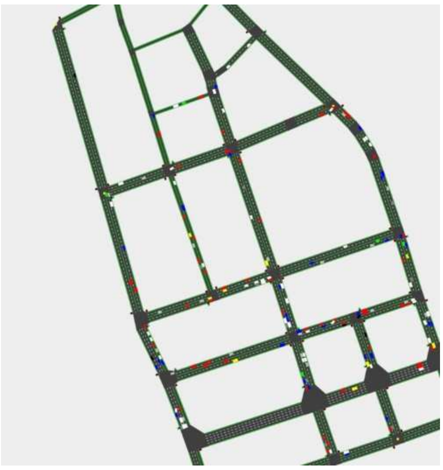

Figure 6 - MATISSE's new 2D Visualizer

5. **Extracted 3D models for the West End section of Dallas**
   No models were provided for this project. We had to *create individual building models* using Google earth 3D maps and add accurate geolocation to each individual model.

6. **Implemented realistic traffic light behaviors using standard traffic light control parameters**
   Defined algorithms to simulate realistic fixed-cycle loops for traffic lights. These algorithms make use of the following parameters:
   - *Phase*: The green interval plus the change and clearance intervals that follow it.
   - *Stage*: Series of non-conflicting phases which run together. A stage starts when the last of the phases commences and then ends when the first of the phases terminates.
   - *Cycle*: The complete rotation through all of the stages.
   - *Cycle length*: The time required for a signal to complete one full cycle
   - *Interstage Period*: The time between the end of one stage and the start of the next stage.
   - *Intergreen Period*: The time between end of a phase and the start of next one

PUBLICATIONS

[1] Saurav Kumar and Nicholas Gans, "Extremum Seeking Control for Multi-Objective Optimization Problems," Proceedings of the IEEE Conference on Decision and Control, December, 2016, *to appear*.

[2] Saurav Kumar and Nicholas Gans, "Towards Fast, Model-Free, Real-Time Traffic Light Optimization," Proceedings of the American Controls Conference May, 2017, *submitted*.

[3] Behnam Torabi, Rym Zalila-Wenkstern and Robert Saylor, "Simulation and Analysis of a Self-Organizing Agent-Based Traffic Light System", The Sixteenth International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2017), *to be submitted*.