Final Report: Visualization and Analysis of Multi-Robot Simulations

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I. Introduction

The frontiers of multi-agent robotics continually evolve as researchers discover new ways to enable teams of robots to collaborate. Due to the expenses involved in working with hardware, much robotics research is performed in simulation. Robotics researchers spend a significant amount of time preparing, running, and analyzing data from simulations, and while the autonomy of their simulated robots may be streamlined, their data analysis is not.

A. How is this done today? What are the limits of current practice?

To analyze large amounts of simulation data, researchers expend significant amount of time and effort to select parameters and metrics to plot, write plotting scripts, then generate and view thousands of plots to identify relationships.

II. Problem Definition

A. What are we trying to do?

This tool compares the effects of various factors that impact the results of multi-agent simulations and provides an interactive overview of the data that helps the user decide whether they need to run more simulations, and if so, with what sets of simulation-affecting values.

We introduce here an interactive tool that offers a visual overview of how parameters varied in batch runs of multi-agent simulations impact the simulation's metric values, as well as presents preliminary statistical analysis using the data to assist the user in identifying which parameters are most or least impactful with regard to the metrics.

As a case study, we demonstrate the use of this tool in analyzing data from a simulation of predator-prey interaction; details of this simulation are provided in Section III, and the analysis results are presented in Section V-A. All simulations were run in SCRIMMAGE, an open-source multi-agent simulator [1]; Figure 1 shows a simulation screen shot.

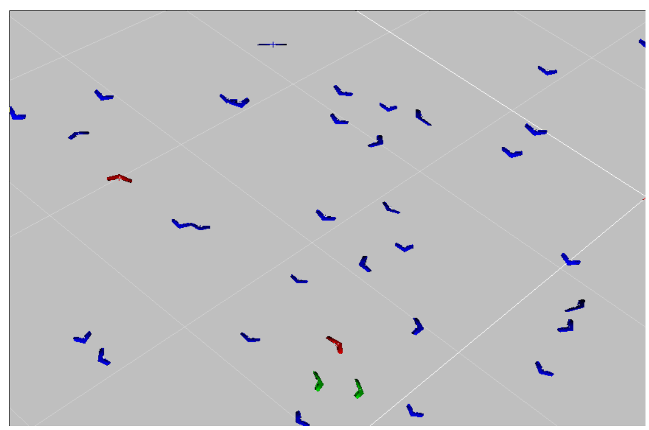

Fig. 1. A predator-prey simulation running in SCRIMMAGE. Predators are red and green, and prey are blue.

III. Background and Literature Review

We base the prey agents in our simulations on [2], and the predator-prey interaction is a simplification of the model in [3]. A predator "captures" its prey if it comes within $5\,\mathrm{m}$ of it, and prey try to evade predators.

A. Multiagent Biological Modeling

Most agent models are very simple, but in swarms, agents can exhibit complex behavior [2]–

[5]. When modified to accommodate real-world imperfections (e.g. sensor noise), these simple models are still effective.

Like these predator-prey models, multi-agent systems are often inspired by collective animal groups behaviors. While our predator-prey simulations incorporate no inter-agent communication, no collaboration, and no learning, many bio-inspired models do [6] [7] [8] and Yong [9].

A number of works regarding predator-prey interaction [10]–[14] indicate that factors such as predator-to-prey ratio, relative agility, and relative speed have significant impacts on how well prey can avoid predators. SCRIMMAGE has the ability to vary these and other factors when running simulations.

The analysis presented in many biological studies provides useful perspective for multi-agent robotics researchers. [15] investigates ant colony defense using Principal Component Analysis (PCA), looking at colonies' behavioral responses to different types of intruders. As the features extracted by PCA are not typically meaningful to the data analyst, however [16], [17], we do not plan to take this approach in our analysis tool.

B. *Statistical Analysis of Big Data*

Drawing conclusions from large volumes of data is difficult due to the limits of human working memory [18]. It is therefore important to find out as soon as possible whether relationships in the data differ from random samples [19], [20]. This does not identify all relationships, but indicates whether analysis on existing data is worth the effort.

After establishing that the data exhibits non-trivial relationships, techniques such as clustering (e.g. k-means [21], [22], DBSCAN [23]) and attribute relevance analysis can be used to simplify what the user sees [22], [24]. From this simplification, however, some information is naturally de-emphasized.

Chronodes [25] is an application of clustering, sequence analysis, and visualization to health data. Medical researchers use Chronodes to understand events associated with a patient's smoking episodes by visualizing event sequences and how the patient's event sequences compare to those of other patients. These techniques could be applied to multi-agent simulation data to capture salient behavior and event sequences.

IV. Approach

A. *What is new or novel about our approach? Why do we think it will work?*

The tool we have developed was designed to reduce effort and potential for error in analysis of simulation data, utilizes statistical analysis and feature selection techniques to compute which simulation parameters impact results most and whether additional data would increase statistical confidence. Python and Pandas were used for data aggregation and cleaning [26], R [27] and several R packages [28]–[36] for statistical analysis and data manipulation, and Shiny and Shinydashboard [37], [38] for the interactive aspects of the tool.

B. *List of Innovations*

The innovations that comprise this project are as follows:

- Interactive user-centric analysis of multi-agent simulation data
- User feedback about which parameters could statistically benefit from additional simulations
- Dynamic visualization of metrics against parameters to visually impart to the user the impact of each parameter

C. *Overall Workflow*

The workflow of this analysis and visualization tool is illustrated in Figure 2.

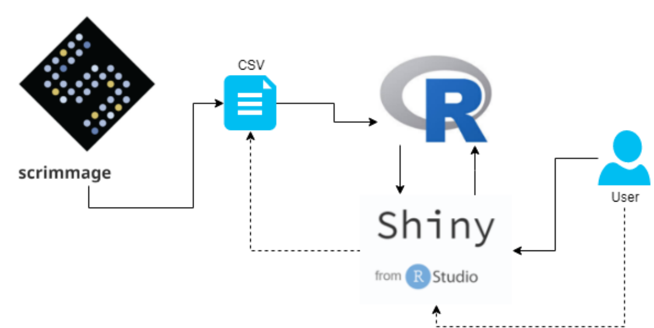

Fig. 2. Diagramming how the data flows through our project. The solid black lines represents the data flowing from SCRIMMAGE and ending as the default data in the Shiny app. The dotted black line indicates that the user can upload a new file through Shiny to use in the tool.

The initial input to our work-flow is the raw data output from SCRIMMAGE simulations. We utilize a Python script and the Pandas package to aggregate the metric and parameter data corresponding to each simulation run into a single CSV file. An additional Python script specific to the predator-prey simulation scenario removes unnecessary columns from this data and cleans it; in future work, this will be more customizable and will be executed via an interactive user interface. At this point, the data can be uploaded to an external Relational Database system.

We were originally planning to incorporate a relational database system to store and allow access to the data through a Java based RESTful API wrapper and web interface that enables individuals to browse individual simulation records. While the Java based system is set up, we currently do not have it hooked up to the rest of the system. Incorporating this system into the R backend remains as future work. One of the challenges to be solved with working with the data involve updating the objects and table schemas whenever the data changes. Such flexibility is to be expected as researches add and remove fields. Our current analysis of the database tools indicate that a schema-less NoSQL database may be a better fit for dealing with data with non-fixed columns. Such column flexibility is not afforded by traditional Relational Databases. In addition, we found that modelling data entries as objects in statically typed languages such as Java were a poor fit for rapidly changing data. This was because each column name change would require a code change. One possible work around for this would be to store each entry as a flexible hashmap. However this would reduce the performance boost typically associated with statically typed languages.

It appears that statically typed languages, may be a better fit for more mature data flows that require fewer column changes.

The interactive visualization, a demonstration of which is shown in Figure 3, allows the user to view scatter or box plots of the parameters varied in simulation with respect to their selected metric variable. The user can then constrain the ranges or discrete values of the remaining parameters that were varied in simulation to be plotted. This effectively allows them to select a single slice or small set of slices of the multidimensional space of parameter combinations to view.

The analysis module, built in R, requires the user to upload the data in csv format and specify result columns, numeric variable columns, and categorical variable columns. The aggregated, cleaned data, these column specifications, and the name of the target/output variable column are the only input the user must provide to begin analysis. Following this user input, the data is further cleaned and transformed by the removal of uninformative columns and rows with missing values. When model fitting options are used, the tool automatically partition the data into training and test set. Once this preprocessing is complete, the analysis module offers simulation stability analysis and statistical analysis. Stability of simulation output is show in a form of table where users can observe the convergence of simulation results. Users also can fit various statistical or datamining models such as multivariate linear regression, random forest regression, and neural networks. Each method provides useful insights to users by evaluating significance of each feature and showing relationship between features and outcome variables in anayltical forms. A user interface built in Shiny [37] allows users to select which statistical methods to apply to the data, select response variables to predict in terms of explanatory variables, and, finally, visualizes the selected analysis results after training and evaluating the selected model.

D. Analysis Methods

A number of modeling and analysis options are available for use through the tool.

a) Correlation Analysis:: The correlation analysis (for numeric variables) module, demonstrated in Figure 4, shows whether there is significant correlation between any pairs of numerical parameters or target variables. The table is visualized using color and size of symbols representing the size of correlation to help users.

b) Stability Analysis:: The stability analysis module, shown in Figure 5, shows the mean, standard deviation, and coefficient of variation (COV) of output values for each set of parameter values, along with the number of simulations run for each unique parameter loadout. Large variance of COV indicates that the simulation output is mostly determined by randomness of simulation rather than parameter values. To obtain stability or convergence in the results, users who see a large COV in this tab may wish to examine their simulation setup for miscalibrations or mistakes, or, if the simulation is properly calibrated, can run additional simulations.

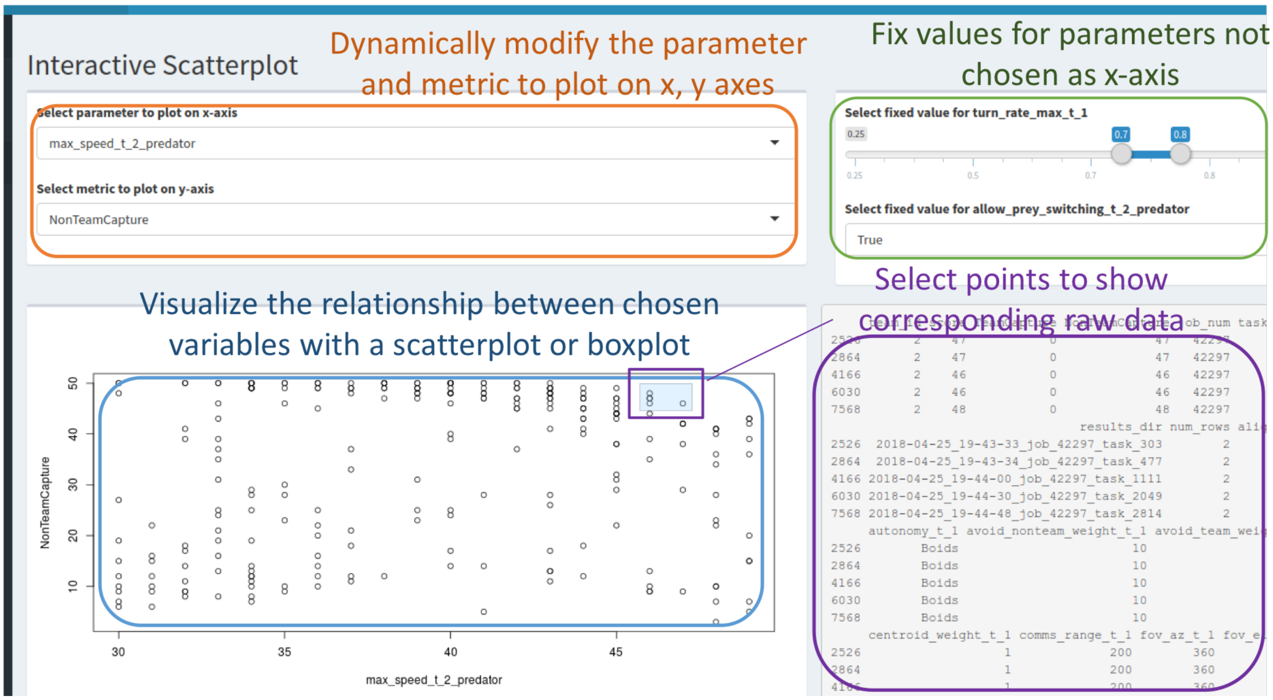

Fig. 3. A screenshot of the interactive visualization tab, annotated to highlight the key features.

c) Analytical Models:: Several regression models and datamining tools are offered for users to select and analyze the data. In this part, the tool partition the data into training and test set. Each model is fitted on a tool-selected training set and predictions made using the reserved test set. Using this tool, users can gain a better understanding of the impact of the parameters on the output variable and discover which, if any, parameters must be more thoroughly explored.

The following models are included as options:

1) Multivariate linear regression (shown in Figure 6)
2) Principal component regresson (using PCA)
3) Partial least squares
4) Random Forest Regression
5) Neural networks

d) Dashboard Interface: The user interface was developed using R's Shiny package [37] and shinydashboard [38]. tool's interactive user interface. The interactive dashboard, the interactive visualization component of which is shown in Figure 3, is a dynamic web-portal that translates Shiny UI functions into more complex HTML elements, such as text inputs, interactive plots, and selection boxes. This dashboard offers the user the ability to quickly explore possibilities for different applicable analyses.

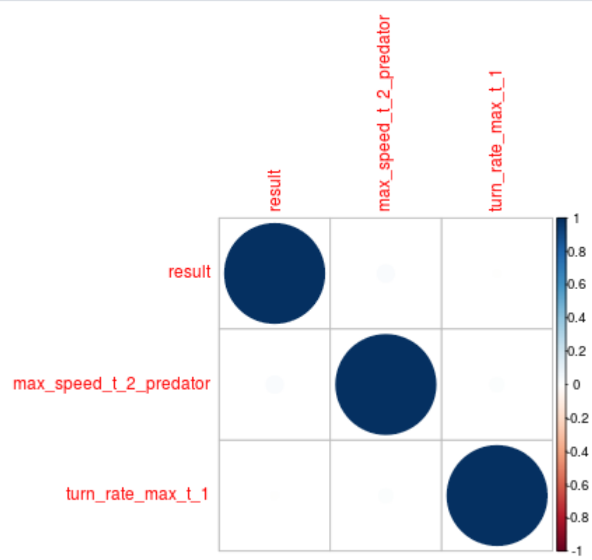

Fig. 4. This correlation plot shows that there is little correlation between the maximum speed of the predators, the turn rate of the prey, and the output variable. Negative correlation, if it were present, would show as red circles, and positive correlation shows as blue circles.

Stability Analysis

Show 25 entries Search:

max_speed_t_2_predator	turn_rate_max_t_1	allow_prey_switching_t_2_predator	N	mean	sd	cov
40	0.75	true	1000	21.411	23.051626	1.076625
40	1.00	true	1000	21.362	23.009746	1.077134
40	1.25	true	1000	21.230	22.927991	1.079981
40	1.50	true	1000	20.935	22.653520	1.082088
40	0.25	true	1000	19.747	21.413209	1.084378
50	1.50	true	1000	13.454	15.865169	1.179216

Fig. 5. A screenshot of the stability analysis module analyzing one of the predator-prey simulation datasets. N is the number of simulation runs in the dataset that all share a given unique set of parameters. The mean column provides the mean of the target result for that parameter loadout, sd is the standard deviation of the distribution of the results, and cov is the coefficient of variation. In this case, the large standard deviations and COVs $> 100\%$ indicate that additional simulations need to be run; the results are dominated by stochasticity.

E. Who cares? What difference does it make if you are successful?

Researchers tasked with analyzing large volumes of multi-agent simulation data will draw conclusions more efficiently than if they were to analyze their data manually.

F. What did this project cost?

This project cost only time and effort.

G. What are the risks?

We risk biasing the end user's interpretation of their data, but have done our best to mitigate this risk in the time alloted to us. In the analysis methods used, R outputs console messages indicating some conditions under which misleading conclusions may be drawn, which can help the user to interpret the results. The analysis methods and overviews both help the user draw meaningful conclusions and decide whether they need to run additional simulations to ensure their results are statistically significant.

H. What are the midterm and final "exams" to check for success?

We measured our success in this project using the checks in Table I. We are able to generate plots from data and use the selected analytics algorithms with them, and the interactive data exploration functionality is clear, functional, and user-friendly. While the tool cannot yet go so far as to suggest more parameter sets for which to run simulations, the tool provides enough information to the user to enable the user to make informed decisions regarding whether to run additional simulations.

TABLE I
SUCCESS CHECKS

Milestone	**Check**
Midterm	Can we generate plots from sample data? Have we selected realistic analytics algorithms?
Final	Is interactive dataset exploration clear and functional? Can tool suggest more parameter sets to run in simulation?

V. EXPERIMENTS AND EVALUATION

There are two big questions that our experiments are designed to answer: what insights have we gained about the predator/prey model we are simulating, and what do users think of our visualization tool.

A. Predator/Prey Experiments

Based on the multivariate linear regression analysis shown in Figure 6, both the prey turn rate and the predators' ability to switch targets before their existing target is captured are statistically significant. Based on the stability analysis, however, additional simulations must be run; as Figure 5 shows, the coefficients of variability of the results are quite high, indicating that the results vary greatly and are

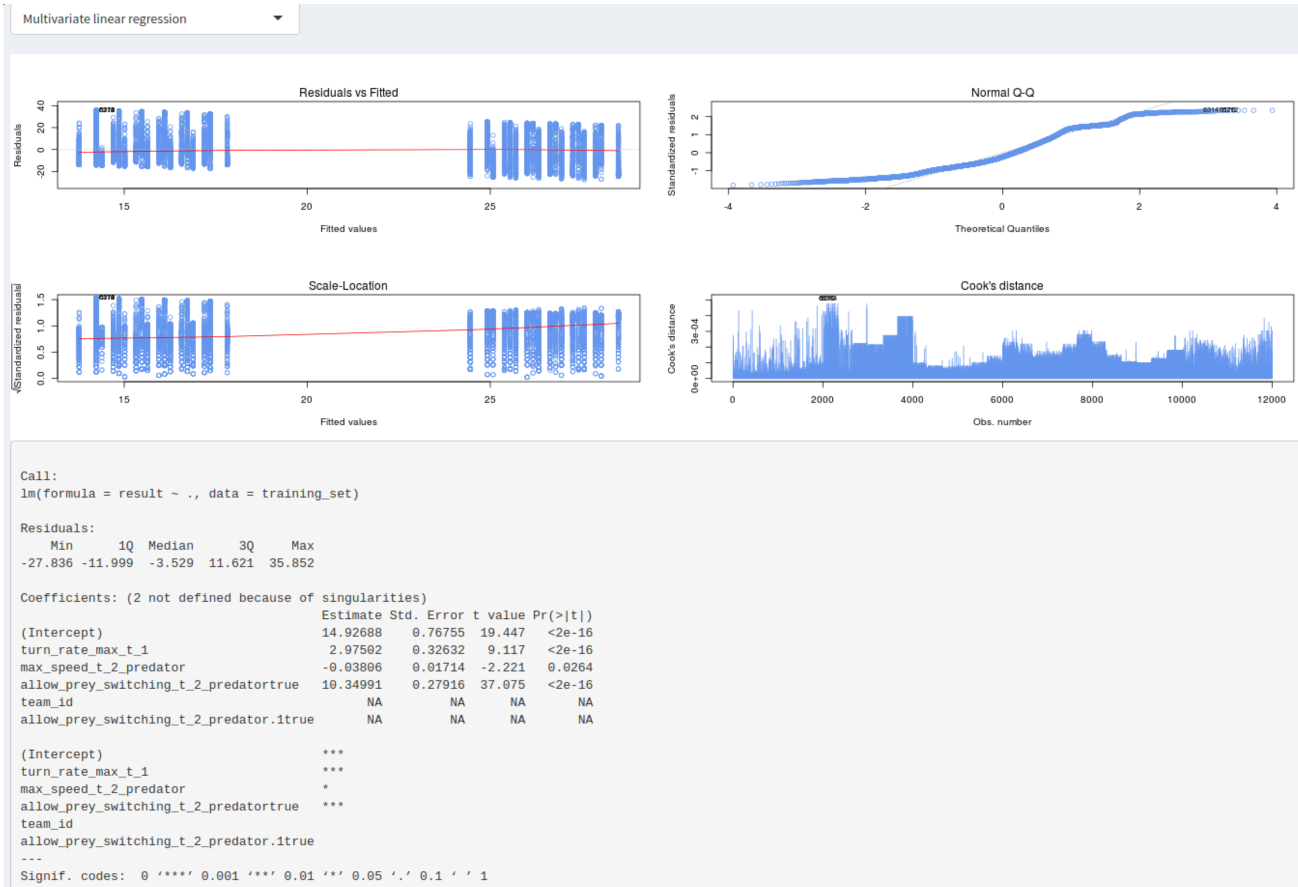

Fig. 6. A screenhsot of the modeling module after performing multivariate linear regression analysis. The results indicate that the prey turn rate and the predator team's members' ability to switch targets are both very statistically significant with respect to the output variable.

likely dominated (with the current number of runs) by stochasticity in the simulation.

B. Visualization Tool Evaluation

Three SCRIMMAGE users were given a demonstration of our tool, then were asked the following questions with answer choices on a scale of 1-5, with 1 denoting "highly disagree" and 5 denoting "highly agree". The average responses are plotted in Figure 7. The users overall liked the tool, with the average agreement to our statements being between neutral and agree.

1) This tool was easy to use.
2) This tool will save me time in my typical analysis workflow.
3) If I need figures for future reports based on experiments in SCRIMMAGE, I would want to use this tool to make them.
4) I enjoyed using this tool.

The users also gave us feedback and criticism that we would like to incorporate into the tool as future work. Dr. Kevin DeMarco, the lead SCRIMMAGE developer, discussed with us that he feels the tool is very useful right now and is something he would use, and suggested that we include sections where users could write their own scripts within the website in case they need to make small

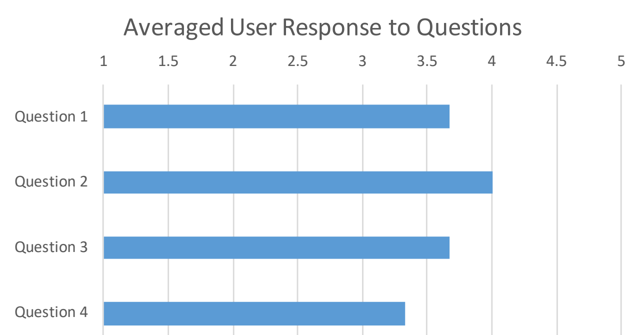

Fig. 7. Averages of the responses to the usability survey questions. A rating of 1 is "highly disagree," and a rating of 5 is "highly agree." The users tended towards feeling between neutral and agreement on these statements.

changes or test an algorithm. Other users suggested various UI enhancements and ways to make usage clearer, including more color and presenting the label names without special characters such as underscores. Lastly, users who were unfamiliar with our statistical tools felt that they did not understand the information being presented, so they suggested that we could provide more information about the analysis.

VI. Conclusion

We believe that we have created a good first iteration of a tool for SCRIMMAGE data visualization and analysis. With the feedback users have provided, we believe that there are improvements we can make to the tool as a second iteration, and we hope that the tool will truly incorporate itself into the workflow of researchers at GTRI. In terms of analyzing the data, we found that parameters such as the max turn radius and max velocity of the predators were statistically significant, measurable affect on the final score of the simulation - a conclusion that would have been more difficult to draw and present without our tool.

VII. Distribution of Team Member Effort

All team members contributed equally to the progress report and project progress thus far.

VIII. Source Code

The source code can be found at https://github.com/laurathepluralized/multi-agent-data-analysis.

IX. Acknowledgements

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References

[1] K. DeMarco and E. Squires, "SCRIMMAGE (Simulating Collaborative Robots in Massive Multi-Agent Game Execution)," Aug. 2017. [Online]. Available: https://www.scrimmagesim.org/

[2] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," *ACM SIGGRAPH Computer Graphics*, vol. 21, no. 4, pp. 25–34, Aug. 1987. [Online]. Available: http://portal.acm.org/citation.cfm?doid=37402.37406

[3] S. I. Nishimura and T. Ikegami, "Emergence of Collective Strategies in a Prey-Predator Game Model," vol. 3, no. 4, pp. 243–260. [Online]. Available: https://doi.org/10.1162/artl.1997.3.4.243

[4] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and Cooperation in Networked Multi-Agent Systems," vol. 95, no. 1, pp. 215–233.

[5] I. Scharf, O. Ovadia, and S. Foitzik, "The advantage of alternative tactics of prey and predators depends on the spatial pattern of prey and social interactions among predators," *Population Ecology; Tokyo*, vol. 54, no. 1, pp. 187–196, Jan. 2012. [Online]. Available: https://search.proquest.com/docview/910714512/abstract/BE457344AFA04F60PQ/1

[6] S. Berman, Q. Lindsey, M. S. Sakar, V. Kumar, and S. Pratt, "Study of group food retrieval by ants as a model for multi-robot collective transport strategies." MIT Press Journals, 2011. [Online]. Available: https://asu.pure.elsevier.com/en/publications/study-of-group-food-retrieval-by-ants-as-a-model-for-multi-robot-

[7] G. T. Cooke, E. G. Squires, L. G. Strickland, K. P. Bowers, C. E. Pippin, T. P. Pavlic, and S. C. Pratt, "Bio-inspired nest-site selection for distributing robots in low-communication environments," in *Distributed Computing and Artificial Intelligence*. Springer, 2018, to appear.

[8] M. Tan, "Multi-agent reinforcement learning: Independent vs. cooperative agents," in *Proceedings of the tenth international conference on machine learning*, 1993, pp. 330–337.

[9] C. H. Yong and R. Miikkulainen, "Cooperative coevolution of multi-agent systems," *University of Texas at Austin, Austin, TX*, 2001.

[10] R. A. Martin and N. Hammerschlag, "Marine predator–prey contests: ambush and speed versus vigilance and agility," *Marine Biology Research*, vol. 8, no. 1, pp. 90–94, 2012.

[11] R. Isaacs, "Games of Pursuit," RAND Corporation, Santa Monica CA, USA, Tech. Rep. P-257, Nov. 1951. [Online]. Available: https://www.rand.org/pubs/papers/P257.html

[12] ——, "Differential games i: Introduction," RAND Corporation, Santa Monica, CA, Research Memorandum RN-1391, Jan. 1954. [Online]. Available: https://www.rand.org/pubs/research_memoranda/RM1391.html

[13] ——, *Differential games: a mathematical theory with applications to warfare and pursuit, control and optimization*. Mineola, N.Y: Dover Publications, Inc., 1999.

[14] J. M. Jeschke and R. Tollrian, "Prey swarming: which predators become confused and why?" *Animal Behaviour*, vol. 74, no. 3, pp. 387–393, 2007.

[15] I. Scharf, T. Pamminger, and S. Foitzik, "Differential response of ant colonies to intruders: Attack strategies correlate with potential threat," vol. 117, no. 8, pp. 731–739. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1111/j.1439-0310.2011.01926.x/abstract

[16] H. Hotelling, "Analysis of a complex of statistical variables into principal components." *Journal of educational psychology.*, vol. 24, no. 6, pp. 417–441, 1933. [Online]. Available: http://prx.library.gatech.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=pdh&AN=1934-00645-001&site=ehost-live

[17] S. Wold, K. Esbensen, and P. Geladi, “Principal component analysis,” *Chemometrics and intelligent laboratory systems*, vol. 2, no. 1-3, pp. 37–52, 1987.

[18] J. N. Rouder, R. D. Morey, N. Cowan, C. E. Zwilling, C. C. Morey, and M. S. Pratte, “An assessment of fixed-capacity models of visual working memory,” *Proceedings of the National Academy of Sciences*, vol. 105, no. 16, pp. 5975–5979, Apr. 2008.

[19] P. W. Glynn and D. L. Iglehart, “Simulation output analysis using standardized time series,” *Mathematics of Operations Research*, vol. 15, no. 1, pp. 1–16, 1990.

[20] D. Goldsman, “Simulation output analysis,” in *Proceedings of the 24th conference on Winter simulation*. ACM, 1992, pp. 97–103.

[21] S. Lloyd, “Least squares quantization in PCM,” *IEEE Transactions on Information Theory*, vol. 28, no. 2, pp. 129–137, Mar. 1982.

[22] S. J. Russell and P. Norvig, *Artificial Intelligence: A Modern Approach*, 3rd ed. Prentice Hall, 2010.

[23] M. Ester, H.-P. Kriegel, J. Sander, and X. Xu, “A density-based algorithm for discovering clusters in large spatial databases with noise.” AAAI Press, 1996, pp. 226–231.

[24] J. Han, J. Pei, and M. Kamber, *Data mining: concepts and techniques*. Elsevier, 2011.

[25] P. J. Polack Jr, S.-T. Chen, M. Kahng, K. de Barbaro, M. Sharmin, R. Basole, and D. H. Chau, “Chronodes: Interactive multi-focus exploration of event sequences,” *arXiv preprint arXiv:1609.08535*, 2016.

[26] W. McKinney, “Data structures for statistical computing in python,” in *Proceedings of the 9th Python in Science Conference*, S. van der Walt and J. Millman, Eds., 2010, pp. 51 – 56.

[27] R Core Team, “R: A Language and Environment for Statistical Computing.” [Online]. Available: https://www.R-project.org

[28] M. Dowle and A. Srinivasan, “data.table: Extension of ‘data.frame‘,” 2017, r package version 1.10.4-3. [Online]. Available: https://CRAN.R-project.org/package=data.table

[29] G. Grothendieck, “sqldf: Manipulate r data frames using sql,” 2017, r package version 0.4-11. [Online]. Available: https://CRAN.R-project.org/package=sqldf

[30] H. Wickham, “The split-apply-combine strategy for data analysis,” *Journal of Statistical Software*, vol. 40, no. 1, pp. 1–29, 2011. [Online]. Available: http://www.jstatsoft.org/v40/i01/

[31] H. Wickham, R. Francois, L. Henry, and K. Mller, “dplyr: A grammar of data manipulation,” 2017, r package version 0.7.4. [Online]. Available: https://CRAN.R-project.org/package=dplyr

[32] H. Wickham and J. Bryan, “readxl: Read excel files,” 2018, r package version 1.1.0. [Online]. Available: https://CRAN.R-project.org/package=readxl

[33] T. Wei and V. Simko, *R package ”corrplot”: Visualization of a Correlation Matrix*, 2017, (Version 0.84). [Online]. Available: https://github.com/taiyun/corrplot

[34] A. Liaw and M. Wiener, “Classification and regression by randomforest,” *R News*, vol. 2, no. 3, pp. 18–22, 2002. [Online]. Available: https://CRAN.R-project.org/doc/Rnews/

[35] J. Tuszynski, *caTools: Tools: moving window statistics, GIF, Base64, ROC AUC, etc.*, 2014, r package version 1.17.1. [Online]. Available: https://CRAN.R-project.org/package=caTools

[36] B.-H. Mevik, R. Wehrens, and K. H. Liland, *pls: Partial Least Squares and Principal Component Regression*, 2016, r package version 2.6-0. [Online]. Available: https://CRAN.R-project.org/package=pls

[37] W. Chang, J. Cheng, J. Allaire, Y. Xie, and J. McPherson, “Shiny: Web Application Framework for R.” [Online]. Available: https://CRAN.R-project.org/package=shiny

[38] W. Chang and B. Borges Ribeiro, “Shinydashboard: Create Dashboards with ’Shiny’,” 2018. [Online]. Available: https://CRAN.R-project.org/package=shinydashboard