Modeling Complex Adaptive Systems as if They Were Voting Processes — Papers from the AAAI 2011 Spring Symposium (SS-11-08)

Voting Theory, Data Fusion, and Explanations of Social Behavior

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Abstract

The challenge of using communications infrastructure to stabilize other infrastructures is related to research on the collective communications systems in social animals, robots, and human-non-human interaction. In these systems, voting models can explicate patterns of observed behavior or predict collective outcomes. Developing more theoretical deductive explanatory power can increase our knowledge about the interplay of voters and communication that produces collective inferences. This paper suggests that many analyses of voting patterns have not integrated what is known about the predictive properties of voting processes into their analyses. Taking a more deductive approach enables us to think about the strengths and weaknesses of existing explanations and imagine new types of analysis that have implications for engineering communications systems to stabilize other infrastructures.

I. Introduction

One of the current challenges in engineering is to develop more resilient and sustainable critical infrastructures by using one infrastructure to stabilize another infrastructure. In this work, multiple agents, human or robot decision makers, communicate collectively in adaptive control mechanisms to regulate stability in electrical grids (Urken, 2010). Analytic research with agents has demonstrated that multiple robot voters, based in centralized or decentralized network relationships, can monitor and pro-actively adjust a voltage line to avoid breakdown.

In these adaptive mechanisms, "agents" can be classified as robotic nodes or hardware systems that play a voting role in the electrical network. In systems composed of social animals, humans, or combinations of robotic, social animal, and humans, the logical properties of voting behavior can be used to model the collective decision-making process: agents communicate votes across a network and the data — votes—are fused into a collective outcome (Seeley and Visscher, 2004; Seeley, 2010; Urken, 1988, 1990, 2010).

Voting systems define how information will be expressed with votes to indicate cardinal, ordinal, and nominal preferences or decisive or fuzzy judgments. Then the voting data are communicated to a vote-counting agent in a centralized or decentralized network and fused into a collective outcome using aggregation or quorum requirements.

At a systems level, the fusion of vote data to control voltage stability in an electrical grid is very similar to what goes on among social animals, agents that make a wide range of decisions to adapt to changing conditions that threaten the sustainability of their group. In groups of humans, robots, and social insects, members communicate to create collective inferences that allow them to take appropriate action (Marshall et al, 2006). "Social animals" may vote with their feet (or their wings), but they act as if they were following voting system rules: they communicate to form collective outcomes using votes to express preferences and judgments (Seeley and Visscher, 2004; Seeley, 2010; Smith, 2006). Although each type of agent has different cognitive abilities and constraints on communications capabilities, comparing human and animal behavior can be instructive for enabling us to appreciate opportunities for cross-fertilization between empirical studies and theoretical interpretations of voting processes. For voting systems provide abstract structures in which subsystem interaction patterns can be discerned to gain a better understanding of complex dynamics.

This paper describes elements of voting system taxonomy that have been identified in research on human behavior and applies them to empirical questions and theoretical possibilities found in current research on voting in social animal and robotic cultures (Schiff, Sudderth, and Goldberg, 2009). Conventional voting system classification is extended to include collective time-to-decision as a property of voting processes. This property raises the possibility that quorum sensing in social animals can be understood as if it incorporated a natural time advantage gained from using data fusion technique that overcomes communication delay and breakdowns and decision maker error.

The paper is structured as follows. Section II briefly describes some key properties of voting systems and relates them to known patterns of fusing vote outcomes. Section III addresses the analysis of "time" in voting processes, highlighting the effects of voting system structure on time-to-decision. Section IV shows how some explanatory problems in voting in social animals and robots can be analyzed with a theoretical knowledge of voting systems. Section V highlights man-machine or human-animal-robotic collaborative decision making as a means of designing cooperative fault tolerance mechanisms. And Section VI discusses ideas for extending our knowledge of social animal decision making and developing new approaches to stabilizing critical infrastructures.

II. What is a Voting System?

For many people, a voting system is simply a device for collecting votes so that they can be counted by an agent—machine and/or human—at a central network location. Or each voter can send its votes to every other peer agent and each peer can fuse the results to reach a collective inference. Frequently, the origin of the theoretical study of voting systems is associated with the work of Kenneth Arrow (1963): the "paradox of voting" and the axiomatic impossibility theorem allegedly limiting the effectiveness and efficiency of majority rule.

But a broader perspective reveals that theoretical properties of voting systems were being discovered hundreds of years before Arrow's work. Even though there was little cumulative knowledge passed on from one author to another, pre-modern voting theory terminology used the term "fusion" to describe the process of aggregating and counting votes to find the outcome. In fact, "social choice" is a term invented by Arrow in his exploration of the social welfare implications of collective choices. Moreover, analysts were aware that communication system noise could prevent accurate computation of the collective outcome. For example, in the French Academy of Sciences, scientists, including the Marquis de Condorcet, perhaps the most frequently cited—but least read—voting theorists, criticized "voice voting" because it too noisy to permit accurate and precise counting of votes. He and his colleagues celebrated "*election au scrutin*," carefully counting marks on paper ballots, which, in the 18th century, was a technological innovation (Urken, 1991, 2008).

In the 21st century, interpreting voting as a data fusion process is a useful starting point for considering how data—votes—represent individual voter preferences and judgments. These data are communicated and fused across network structures. Votes can be communicated to a central host to be fused using a quorum or aggregation stopping rule for forming a collective outcome. Alternatively, in a decentralized or peer-to-peer network, each voter sends its votes to every other peer and each peer processes its received votes to fuse them into a collective outcome with its own votes.

The systems that structure voting processes consist of inputs and outputs with ideal or predictable properties. Although the principle of one voter, one vote (OVOV) is often taken as a necessary or desirable property for inputs, other more complex, "democratic" representations of voter input include ordinal or ratio scoring of all the choices in a voting agenda. (For example, Borda voting reveals collective ordinal relationships in collective outcomes while Condorcet and Copeland scoring compute ratio comparisons of choices in collective outcomes. (Urken, 1991, 2005) Understanding the logical relationships between voting inputs and outputs is a major theme in the study of voting systems. This analytical focus has been responsible for the discovery of the so-called "paradox of voting" (an inconsistency between transitive individual preferences and intransitive collective outcomes).

Historical research shows that the so-called "jury theorem," a label invented in the twentieth century by Black (1954) to describe Condorcet's 1785 *Essai sur l'application de l'analyse à la probabilité des decisions rendues à la pluralité des voix* (Condorcet, 1785) on voting theory, is a misnomer. For modern social scientists, Condorcet's probabilistic models of competence in voting made sense only if a jury were voting on matters of fact. However, as Baker (1975) has explained, Condorcet argued that elections were not simply popularity contests or exercises in preference aggregation, but processes of collective judgment to find the best candidate—the correct or "optimal" choice in an election.

As Urken (1991, 2008) has shown, the relation between preferences and competence in voting inputs is ambivalent—even in Condorcet's own "paradigm" (or metaphysical research program). Preferences for choices that may be correct must be formed, but the voting process can be modeled—as Condorcet does—with preferences as a random variable.

In the "jury theorem," the voting agenda is binary with each choice equally likely to be correct or optimal. And the probability of producing a correct or optimal collective choice is a cumulative probability. So the model provides no analytic short-run behavioral predictions. In fact, Condorcet's model raises more questions than it answers. For example, if preferences and competencies are no longer independent variables, does voter competence reduce to voter preference or vice versa? Or is there a mediating variable that regulates the interaction of competence and preferences?

III. Time and Voting

The extent to which "time" is useful in explaining the relation between competence and preference inputs and collective outcomes in voting has not been systematically investigated. Why not? Perhaps the most important reason is the historical focus on elections as the context of voting. In this context, time is certainly relevant to the formation of voter preferences/judgments and the casting and counting of votes on or before election day. But time is not a fundamental limiting factor in human communications infrastructure that can produce catastrophic collapse. Despite legal deadlines for casting and counting votes, electoral systems provide judicial adjustment mechanisms for getting more time to scrutinize voting outcomes. Indeed, in some cases, courts can order that elections be repeated if audits do not resolve the interpretation of the collective outcome.

However when telecommunications infrastructure is used as control mechanism for regulating electrical infrastructure, "time" plays a different, less flexible role. If the fusion of vote-data across a telecommunications network does not produce a collective inference in time to take action to restabilize the electrical grid, the consequences can be catastrophic (Urken, 2010). For this reason, frequent collective choices are used to sample conditions in the electrical grid to reach reliable inferences about changing conditions. In this context, models of voting processes based on the average elapsed time for transmitting votes in a network are useful. So are models of voting behavior based on the percentage of outstanding or expected votes collected during a voting process. Although these percentages can vary significantly with the complexity of the voting method used to express preferences and judgments, collection patterns can serve as a useful reference for gauging time in voting processes.

Regardless of voting method, data fusion systems based on voting can be engineered to shorten the time required to produce a reliable collective inference. In "error-resilient data fusion" (ERDF) processes, the properties of the systems used to represent and aggregate votes produce a high probability of producing error resilient collective outcomes (ERCOs). When a voting process produces a reliable ERCO, neither outstanding votes or data, nor unelapsed time, will change the collective inference. So ERCO results provide a basis for ignoring uncollected critical data and enabling agents to take immediate action to adapt to changes in their environment.

Current analytic and applied research on ERDF systems is developing a better understanding the conditions under which ERDF models work as expected. This type of analysis provides insights into the direction and magnitude of changes in the probability of producing an ERCO. Urken (2005) showed that when the reliability or competence of each voter can be measured or estimated, the accuracy of ERCO's can be maximized using the Bayesian techniques to weight individual votes. Moreover, ERDF models can incorporate control factors that could regulate false positive and false negative errors. At the very least, ERCOs can dampen these types of error. At best, ERDF designs could provide increased, unprecedented trustworthiness in engineering design specifications.

Thinking about ERDF systems highlights the pre-vote and post-vote phases of voting processes. The first phase includes the timing of agenda creation while the second phase contains the events that occur if the voting process fails to produce a collective inference. The second phase ends when a new collective decision can be scheduled and carried out.

In human political choices (with divergent interests) the scheduling of voting agendas in human elections can be an opportunity for all sides to try to engage in manipulation of the agenda to favor their chances of victory. And if votes on choices about how to achieve convergent interests are at stake, some manipulation may still be attempted. But despite manipulation, the scheduling of the collective choice is usually under human control. However, in robotic or social animal cultures, agenda scheduling may be constrained by extreme time pressure, even to the point of being a matter of survival.

If and when a voting system fails to produce a collective outcome, human systems provide more flexibility and less uncertainty than is usually found in robotic or social insect cultures. Species survival provides a strong motivation for social animal and robotic behavior. List, Elsholtz, and Seeley (2009) have studied patterns of time in honeybee nest selection and developed a mathematical model that reliably predicts (or retrodicts) time-to-decision. The model measures elapsed time without explicitly modeling the sequence of communication and vote aggregation that produces collective inferences.

ERDF insights have implications for understanding time and agent system designs for robotics, social insects, and man-machine interaction. Perhaps most important, ERDF systems rely on frequent sampling to render collective inferences. In social insects, it is not clear if periodic sampling exists, and if so, how it works. Moreover, if collective sampling is engineered properly, the ERDF mechanism itself can adapt to feedback about failure and avoid failure in its next collective decision. This adaptation might include redesigning the agenda or shifting agendas contingently based on feedback.

Studies of control systems and network communication have revealed that the responsiveness of a control mechanism to failure can be associated with the patterns of failure itself. Sudden and precipitous breakdowns tend to be more catastrophic than failures that gradually and or gracefully lead to systemic malfunction. ERDF functionality may have a role to play in shaping the system failure by increasing the error-resilient window of opportunity so that appropriate responses can be made. In the context of electrical grids, for instance, the spectrum of response includes mobilizing microgrid resources to restabilize a main distribution grid as well as delivering enough power to slow down system collapse to avoid harm to residential and industrial users.

Indirectly, ERDF adaptive controls may affect complex stochastic behavior associated with patterns such as highly optimized tolerance and power laws.

IV. Evaluating Voting Model Explanations

Making indirect inferences about the validity of voting models as explanations of social insect behavior of voting in social insects is a useful experimental technique. Unfortunately, there is no strong evidence that confirms the voting models.

Stronger evidence might be found if the theory behind the models included a more detailed description of the conditions under which the theory can be expected to fail. Theoretical refutations enable a theory to grow through trial and error. To promote such growth, the following issues should be considered:

Preferences

Agenda Complexity: Set up experimental conditions in which the voters can have tied preferences (e.g., in nest relocations, include two or more nests that are of superior quality).

When voters choose among marginally different nest sites, manipulate the differential among choices from small to large and see if indecisive outcomes decrease.

Fuzzy Preferences: Investigate the use of fuzzy preferences (interval utility ratings) to take account of complex voting data and voter cognitive limitations.

Retrospective Analysis: Look retrospectively at the evolution of voter species to determine if groups with larger numbers of voters survive marginally or tend to die out.

Voter Competence (Reliability)

Group Size: Is group performance consistent with the “jury theorem” results when the number of voters increases or decreases in size? Precise and accurate measures of voter reliability or competence are difficult to measure directly. But the difficulty of the voting decision task can be controlled to gauge the expected direction of change in voting inputs to test hypotheses about the probability that a group makes an optimal collective choice. Competence can also be tested by manipulating group size. Historical, retrospective analyses could determine if species that are extinct or dying out may have relied on different group sizes.

If group size effects are found, experiment with environmental challenges that will produce changes in direction and/or magnitude in the probability of making a correct choice.

Make assumptions about competence more explicit. Do all voters have the same probability of making an optimal choice? What assumptions about competence (and group size) would make it reasonable to assume that small groups can perform as reliably as large groups? Take account of the predictions in Grofman’s (1976) analysis of the “jury theorem” that shows the conditions under which a group of voters performs more (and less) efficiently than an average voter.

Time

Concepts of Voting Time: Use elapsed communications time and implicit data collection time to model how long it takes to produce a collective outcome. Compare these results with the theoretical ERDF predictions for different methods of preference and judgment expression and see how well the voting model collective outcome predictions account for patterns of change in direction and magnitude for ERCOs. How are such changes indirectly associated with the time required for carrying out system recovery?

Communications Breakdowns: Introduce environmental challenges and impediments to communication of votes. Do voters take longer to reach a consensus? Or can their shorter time patterns in quorum sensing be explained by ERDF predictions?

Peer-to-Peer Voting: When peer-to-peer communications are observed in social insects (Marshall et al, 2006), is this consistent with peer-to-peer models of voting and data fusion? Do P2P and centralized data fusion operate separately or do insect peers send votes to the central host as well as to each other?

Robustness and Resilience: When animals use a back-up collective choice as a contingency control, what is the time interval between the end of the first collective choice and the second one? And what is the time constraint on the second collective decision? Is there evidence consistent with the hypothesis that ERDF-like behavior accounts for system success? If communication in the first collective choice is degraded, is the voting process slower and/or less optimal for enabling the system to bounce back in time to sustain itself?

Complex System Failure: When voters fail to reach a collective outcome, what is the pattern of collapse? Is it a precipitous collapse or more genteel pattern of degradation? Can the severity of the failure be mitigated if conditions favoring ERCO production are enabled?

V. Inter-Agent Collaborations

Reengineering relationships between humans and other types of agents could expand the scope of cooperation in human-agent interactions and introduce new options for cooperative fail-safe operations.

This opportunity exists in large centralized electrical distribution networks and could exist in more decentralized microgrids or Smartgrids (Urken, 2010). In centralized distribution networks, for example, research on “real-time” updating of the parameters of the system for SCADA (Supervisory Control and Data Acquisition) centers, where human managers can, if time permits, exert control. Currently, parameters for a large network can be updated in less than four minutes. In this SCADA man-machine environment, humans can use visualization and computationally intensive systems to adjust the parameters of the system to enable it to operate robustly. However a large electrical network can *collapse completely* within four minutes, long before humans even attempt to intervene to restabilize the system. In contrast, in microgrids or Smartgrids, decentralized networks for producing and distributing electricity, inferences about the stability of the power system can be proactively reached locally to intervene in time to avoid destabilization. In this mode of operation, agent collective decisions based on ERDF principles can be designed for a spectrum of tasks (e.g.s., controlling voltage, current, etc.). The decentralized system can also be engineered to share the information in these collective inferences with humans in centralized SCADA systems.

An interesting finding of current ERDF research on microgrids is that decentralized data fusion can operate within a distributed network in two modes: 1) a centralized mode in which one of the microgrids acts as a local central host to process vote data, or 2) a decentralized, peer-to-peer (P2P) mode in which *each* peer agent sends its votes to *every other peer* agent and each agent fuses the data into a collective inference (Urken, 2010). Mode 2 operations are remarkably consistent with analysis of social insect behavior (Marshall et al, 2006). In the microgrid model, P2P ERDF could operate with or without centralized data fusion. Research still has not clarified if and to what extent such redundancy contributes to efficient and effective operations. In the social insect model, it is not clear if both types of data fusion are operating or if P2P communication is sufficient. Studying redundancy in robot and natural systems could help us understand the potential advantages and disadvantages of combined P2P and centralized redundancy.

In the microgrid scenario, the role of human agent intervention is contingent on the implications of centralized and P2P processing for engineering the system to enable human agents to intervene if necessary. Intervention may be possible under either mode of data fusion or there may be conditions under which one data fusion mode is game theoretically dominant. Such analysis could be derived from modeling the data fusion process as a differential game.

If time permitted, there might be new options for man-machine agent interaction that would define a human-robot agent collective consensus that would have to be reached to enable the system to continue operation instead of, by default, shifting to a different form of operational procedure. If the consensus were error-resilient, this procedure could provide a model of a fail-safe system that does not depend on one type of agent to necessarily be more reliable than another.

Positive Train Control (PTC) which involves the use of telecommunications to control train traffic, provides an interesting example. In the June, 2008 Metro collision in Washington, D.C., an engineer noticed that his train was about to crash because the automatic control system had apparently failed. When he tried to push the manual override to stop the train, the manual override itself failed. If the robot and the human had been periodically sampling the movement of the train to reach a cooperative, joint consensus on the facts of the situation, an ERDF control might have been engineered to allow time to avoid the collision. And if communication and/or one agent failed to vote, the data fusion system would not have produced a collective inference and the default would have been for the train to stop immediately.

VI. Discussion

Developing a theoretical perspective on modeling and testing of theories of voting behavior based on data fusion allows us to advance our knowledge about the interaction of individual and collective voting properties in centralized and decentralized networks. Traditional models of voting combined with error-resilient data fusion (ERDF) analysis suggest ways of investigating the idea that quorum sensing may be a result of a natural ERDF sensibility in social animals, a characteristic that may have survival and evolutionary value. In particular, an ERDF model might be useful in explaining how social animals get sufficient time to implement a decision once a collective inference has been reached

Although this paper has focused mainly on social insects, the findings have relevance to all artificial designs for humans and robots as well as social insects.

Thinking about voting and time in new ways leads us to imagine other forms of cooperative data fusion. For instance, if social insects were being stressed by conditions that degraded communications, humans might reach error-resilient collective inferences about the stressful conditions and take action to ameliorate the communications system to enable social animals to adapt successfully.

Such possibilities provide an incentive to pay closer attention to the details of how votes are fused. For example, in complex hybrid data fusion processes (involving digital and analog measurement), voting systems can be designed using compound decision rules for expressing preferences and judgments.

Moreover, looking at voting and data fusion in other natural and artificial agent species should lead us to reconsider assumptions about cognition in the literature on voting derived from Condorcet's work. It has already been noted that a voting analytical framework enables explicit modeling of false positive and false negative choices as attributes of individual voters. But even this more detailed model of voter behavior does not address the question of the role of chance in voting for a correct choice. It may be that we can learn from social animals that have survived and evolved to the point where chance plays an insignificant or at least a non-destabilizing role in determining collective inferences.

All of these issues are associated with understanding how well communications infrastructure is used to regulate the stability of other infrastructures. In ecology and biology, robustness (the ability to function normally despite disturbances) and resilience (the ability to respond to respond to potentially catastrophic disturbances) by managing system degradation and recovering quickly once a disturbance has ended) are sometimes used interchangeability. Understanding fusion of voting data across of spectrum of agents may contribute to clarifying the differences between engineering robustness and resilience and similar attributes in human and other agents.

Looking at voting behavior across types of agents may also help humans learn how to transfer bio-inspired designs to a human or robotic context

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