Judgment Aggregation for Cooperative Anchoring on the NAO Robots

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Abstract. Cooperative anchoring is the sharing of associations between symbols and sensor data across multi robot systems. We apply the solution of Judgment Aggregation, a logic based collective-decision making framework from social choice theory to the problem of cooperative anchoring in terms of information fusion. We model a multi-agent system comprising of NAO robots on a search exercise using its vision and audition sensor into this framework and fuse them by means of aggregation rules and compare them on a truth-tracking basis.

Keywords: cooperative anchoring, collective decision-making, judgment aggregation

1 Introduction

Cooperative anchoring is the process of performing anchoring [3] in systems in which the perceptual data is distributed across multiple agents. This entails ability to represent, communicate, compare and fuse information [5]. Anchoring a complex concept entails combining data from several percepts with existent symbolic knowledge and perceptions in response to a predetermined action. To detect an immobile obstacle, a robot uses vision, sonar sensors and reasoning based on expected percepts in response to its own actions. For *e.g.*, if a robot detects the obstacle, the robot asks the obstacle to move and if it does not detect a response concludes that obstacle is immobile.

The main advantage of using multiple robots in problem solving is the reliability of multiple sources of information or sensors, their possible heterogenity and possibility of anchoring complex concepts. Given that fusing homogeneous sources of information itself leads to contradictory results due to environmental conditions, co-operative anchoring of a complex concept becomes more challenging. One way to tackle this problem of fusing information is to see it and represent it as a multi stake-holder decision problem.

Social choice theory is a theoretical framework for developing and analyzing methods for reaching multiple stake-holders decisions [1]. A non-theoretical example of such a decisions are jury trials, decisions by committee etc. Which social choice method is applied to which decision problem depends on the type of information aggregated, the type of decision needed and the context of the problem, since different methods lead to different social outcomes. For example in presidential elections aggregated are ballots with one candidate choice from a list of candidates and the social outcome is one winner candidate. The method of aggregation is a voting rule which is selected by constitution. The reason why the voting rules are set by constitution is that different voting rules, on the same collection of ballots choose different winners. Voting rules rely on some method of statistically pooling the votes to decide on a winner. The combined perceptual and non-perceptual data is logically related hence one cannot obtain coherent symbolic collective knowledge by statistically pooling the individual anchored symbols. For this type of decision problem we need to use another social choice method, *judgment aggregation*. Judgment aggregation studies how a group of individuals can arrive at a consistent collective set of answers to set of interconnected questions, in that the answers given to some of them constrain the answers that can consistently be given to others [6].

2 Research problem and challenges

We study hot to apply judgment aggregation to the problem of information fusion within the scope of cooperative anchoring.

A judgment aggregation problem is specified by a consistent set of issues represented as propositions called an agenda $\mathcal{A}$, a set of formulas $\mathcal{R}$ representing the relations between the agenda issues, and a set of agents N. A judgment is a valuation that assigns a truth value, often true (a) or false ($\neg a$), to $a \in \mathcal{A}$. A set of judgments is a collection of valuations assigned for each agenda issue. A judgment set is *consistent* if it does not evaluate any of the elements of $\mathcal{R}$ to false, and *complete* if it contains a judgment for each issue in the agenda. A *truth-functional agenda* is an agenda that can conceptually be partitioned into a set of premises and a set of conclusions. Given judgments on the premises, the judgments on the conclusions can be determined using $\mathcal{R}$.

A profile is a collection of judgment sets. A judgment aggregation rule assigns a non empty set of consistent judgment sets to a profile of consistent and complete judgment sets, called collective judgment sets and issues respectively. As with voting rules, different judgment aggregation rules lead to a different collective outcome. The challenge in our research problem is to determine which judgment aggregation rules are suitable for which cooperative anchoring context. How suitable a judgement aggregation rule is evaluated by comparing the results of aggregation or collective anchoring to actual “truth” scenario.

We can distinguish the anchoring context along three dimensions: the homogenity of robots in the system, the way in which the individual anchoring is performed and the nature of the anchored symbol and used data. Along the first dimension we can distinguish between homogenous robots with similar sensors, and non-homogenous systems, including robots, software agents, isolated sensors etc. Along the second dimension we can distinguish between robots that use the same and different information to anchor a symbol, or in judgment aggregation terms, robots that that use different premises (and by extension agendas) and robots that use the same agenda. Along the third dimension we can distinguish between perceptual data and existing symbolic knowledge from the robot’s knowledge base.

To tackle the research problem we need to develop a framework in which individual anchoring can be executed, the robots in the system can communicate their individual anchors and implement judgment aggregation rules. Therefore we begin by setting such a framework and analyze the most simple case of homogenous robots, five NAO robots[1], that perform individual anchoring using the same agenda. We consider an example of a symbol that admits binary values and that is anchored to a set of percepts. Therefore all premises in the agenda are assigned judgments based on perceptual data.

The two basic judgment aggregation rules are the *premise-based procedure*(PBP) and the *conclusion-based procedure*(CBP). To each premise, PBP assigns as collective the judgment supported by more then $\frac{|N|}{2}$ agents and entails the conclusion judgment using $\mathcal{R}$. CBP assigns to each conclusion the judgment supported by the majority and it assigns no collective judgments for the premises. These are the two aggregation rules that we implement and evaluate them with respect to their truth tracking performance.

3 Sound localizing example as a judgment aggregation problem

We consider as an example a scenario in which the robot determines if a sound comes from a box (symbol x). We placed a sound source inside a box in a reasonably large enclosed room. When asked to anchor x, the robot first attempts to detect sound, turns in the direction of the sound and attempts to visually detect a box. If a box is identified it walks towards it and analyzes the change in sound pressure. The sound detection is built around the sound pressure-inverse distance law which states that, assuming a stationary sound source, the sound pressure is inversely proportional to the distance between the source and the listener.

For executing the individual anchoring of x we interface the agent programing language GOAL [4] and the NAO. GOAL allows NAO to be programmed as a rational agent which determines its goals based on its beliefs. The beliefs are formed based on percepts received from the underlying robotic framework (in this case Naoqi) and earlier beliefs. GOAL communicates with Naoqi through a EIS(Environment Interface standard)-compliant Java interface [2]. The interface receives sensor information from the subscribed Naoqi modules, build new percepts to send to GOAL and also executes actions on the NAO. GOAL allows for percept rules to be specified, which read from the percept base to form beliefs. It also allows the development of a multi-agent system and facilitates communication between agent programs.

We model the sound localization as a judgment aggregation problem. The set of agents consists of our five robots $N = \{(Lucy, Rosy, Fonsi, Jempi, Marvin\}$. The agenda consists of premises: *Nao can hear sound with Energy value* E_1 (p), *Nao can see a box at distance L (in the assumed direction of the sound)* (q), *Nao can hear sound second time at* $\frac{L}{2}$ *distance with Energy value* E_2 (r), *Sound energy value* E_2 *increases in proportion to* L(s) and conclusion *Sound is coming*

[1] http://www.aldebaran-robotics.com/

from inside the box (x). The logic relations between the agenda issues are given by $\mathcal{R} = \{(p \wedge q \wedge r \wedge s) \leftrightarrow x, r \rightarrow q, s \rightarrow r\}$. The first formula describes how the conclusion is entailed. The Nao cannot walk to half the distance of the box and hear sound the second time without having seen the box, hence r can occur only if q has occurred. The sound cannot increase in proportion with distance when sound is not heard for the second time or when $E_2 = 0$, hence s can occur only if r has occurred.

4 Experiments, Results and Future Work

To execute the cooperative anchoring we use four GOAL agent programs, the basic GOAL agent program for anchoring *LookandHear*, a co-ordinator and two aggregator programs one implementing the premise-based and the other the conclusion-based judgment aggregation rule as shown in Figure 1. The *LookandHear* program forms GOAL gutter beliefs and is associated with all NAOs present in the environment. These beliefs are sent to the standalone aggregator programs. Thus judgment aggregation is implemented by agents casting judgments as beliefs based on perceptual information and sending the beliefs to centralized aggregators. The *LookandHear* program also receives cues from the *coordinator program* and sends status completion messages to it. Since there is need for sound sensitivity and synchronization between the agents to listen to the same sequence of sound without interference from each other, we have the coordinator program.

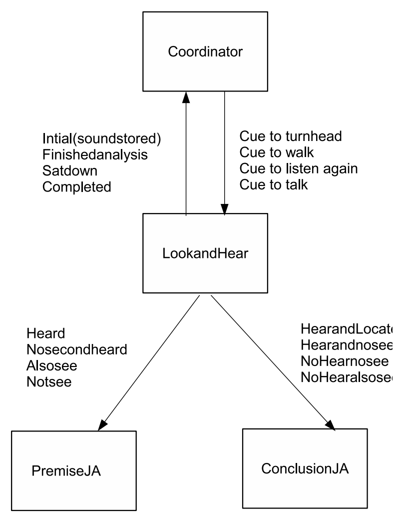

Fig. 1. MAS Recipe

An example of the profiles of judgments involving the five robots, is the profile $P = \{Lucy = \{\neg p, q, \neg r, \neg s, \neg x\}, Rosy = \{\neg p, q, r, s, \neg x\}, Jempy = Fonsi = \{p, q, r, s, x\}, Marvin = \{p, \neg q, \neg r, \neg s, \neg x\}\}$. We obtain $PBP(P) = \{p, q, r, s, x\}$, while $CBP(P) = \{\neg x\}$.

Of the fifty multi-agent scenarios we tested, we observed that thirty of them displayed a different result when the PBP and CBP were used. This can be seen in Table 1, where $I =$"Inside" and $O =$"Outside" and $O(*) =$"Outside, box close to sound source and in same line of vision".

No. of profiles	Inconsistency	Truth	PBP	CBP
25	Y	I	I	O
5	N	I	I	I
10	N	O	O	O
5	N	O(*)	I	I
5	Y	O(*)	I	O

Table 1. Aggregation Results for Profiles

Since the premises are built from different sensor information, an aggregate of all available sensors or premises give a more favorable situation. In this case, the premises are p, q, r and

s. The logical propositions p and r are related to the audition sensor and the proposition q is related to vision. This explains why a simple majority on the premises and application of the logical connection rule to this majority gives a consistent and realistic outcome and the premise based procedure emerges the clear winner.

An important conclusion from the sound localising example is that not all robots are equally reliable *i.e.,* some of them are in a better position to use vision or audition and the judgment aggregation rule used should be weight sensitive. Once an anchor is made, the link between the symbolic representation and the real world object must be maintained. We need yet to implement when and how the robot re-evaluate their judgments.

We need to implement other aggregation methods besides the premise- and conclusion-based rules and analyze their truth tracking ability in the remaining cooperative anchoring contexts.

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