

# Shared Autonomy and Teaming: A preliminary report<sup>\*</sup>

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## ABSTRACT

We outline how an agent's shared autonomy considerations affect its interaction in a team. A unified model of acting and speaking will be presented that includes teaming and autonomy. This model is applied to the domain of satellite constellation. We introduce our simulator and outline our application of autonomy and teaming concepts.

**KEYWORDS:** Multi-agent Systems, Shared Autonomy, Agent Teams

## 1. INTRODUCTION

We have presented Situated Autonomy as a moment-by-moment attitude of an agent toward a goal and have argued that it is a useful notion in modeling social agents [6].

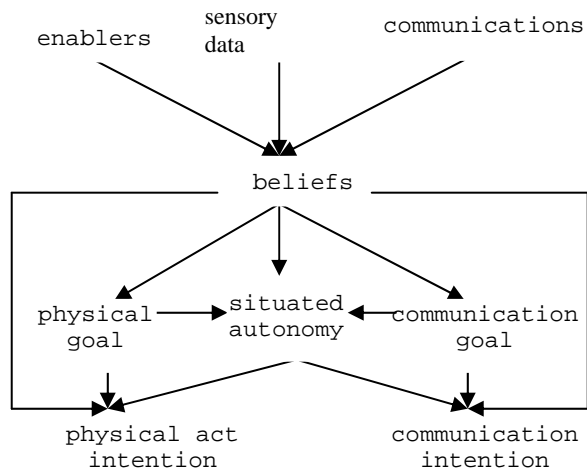


Figure 1 Action Selection

We argued that a combination of the nature and the strength of an agent's beliefs and motivations lead the agent to perceive one of the following: (a) the agent chooses itself to be the executor of the goal, (b) the agent delegates the goal entirely to others, (c) the agent shares its autonomy

with other agents, or (d) the agent has a relatively small and undetermined responsibility toward the goal. Our focus in this paper is when the agent perceives shared autonomy.

Situated autonomy is an important part of an agent's action selection. Figure 1 shows a very simple action selection in Belief Desire Intention (BDI) paradigm and the role of situated autonomy. Along with goals and beliefs, we believe situated autonomy is used in the process of determining intentions. The process can be highly cognitive as in planning or less cognitive as in reaction generation. Enablers are the agent's perception of its own abilities, social factors, tools, and resources.

There are many accounts of starting or joining a team [2, 4, 10]. We favor the ingredients of intentional cooperation laid out by Tuomela: (a) collective goal or plan, (b) strong correlation among member's interest or preferences, and (c) having a cooperating and helping attitude.

We believe that in common situations, an agent's situated autonomy changes at a lot faster pace than its participation in a team. Once an agent perceives shared autonomy toward a goal, it may be inclined to recruit one or more agents to form a team. After a team is formed, the agent's degree of shared autonomy will change at the speed of perceived changes to the cognitive ingredients of situated autonomy. A recruited agent's degree of shared autonomy will be smaller than the recruiter's shared autonomy but after a team is formed will change to any level.

We are developing a model that unifies acting and speaking [7]. This model uses production rules to encode a conversational policy. A conversational policy is a modeling system that is designed to encode a set of conventions shared among a group of agents [5]. Such systems are generally called Normatives [1,10]. A prototypical agent follows the conventions of the group in communicating and sharing mental states. However, situated autonomies of each agent will individualize its interactions and allow it to deviate from the expected behavior.

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We will present a model of conversational model in generic, non-BDI format. Each agent will personalize parts of conversational policy in its own BDI paradigm. A conversation policy is two types of simple production-like structures we will call transitions, shown below.

```
physical condition * spoken word/phrase * speak state
    → speak state
physical condition * speak state
    → spoken word/phrase
```

To model physical actions of an agent in reactive behaviors, we introduce two other types transitions, shown below.

```
physical condition * spoken word/phrase * act state
    → act state
physical condition * act state
    → act
```

A number of agents may share a unified model. For example, a group of agents may share a conversational policy. The shared model becomes their Norm. By entering a model and tracking the shared states, agents can synchronize their actions. Privately, each agent will consider transitions in terms of beliefs or goals, and intentions.

In the general model, physical conditions arbitrate among productions that provide alternative acts or words at a given state. However, each agent will have a personalized perception and interpretation of the physical conditions in terms of beliefs. We consider agents' situated autonomy and teaming consideration is determined by the agent's unique perceptions of the common physical conditions. Below we rewrite the transitions from an agent's perspective and add situated autonomy. 'Physical conditions' and 'spoken word/phrases it hears' are things about which an agent has beliefs. The states are the agent goals (or interchangeably desires). The 'physical act' or 'chosen word/phrase for communication' are the objects of an agent's intentions.

```
Belief(physical condition) *
Belief(spoken word/phrase) *
    Goal(speak)
    → Goal(speak)
Belief(physical condition) *
    Goal(speak) *
    situated autonomy
→ Intention(spoken word/phrase)
Belief(physical condition) *
Belief(spoken word/phrase) *
    Goal(act)
    → goal(act)
Belief(physical condition) *
    Goal(act) *
    situated autonomy
    → Intention(act)
```

The remainder of this paper is organized by working through an example of a unified model and how agents can personalize the physical conditions and consider teaming and changes in their Shared Autonomy. We will present a simulation of a constellation of satellites that can be tasked from ground. We will show our unified model and related issues of learning autonomy level using this application domain. We have not yet conducted experiments with situated autonomy and hence we consider this report a preliminary report.

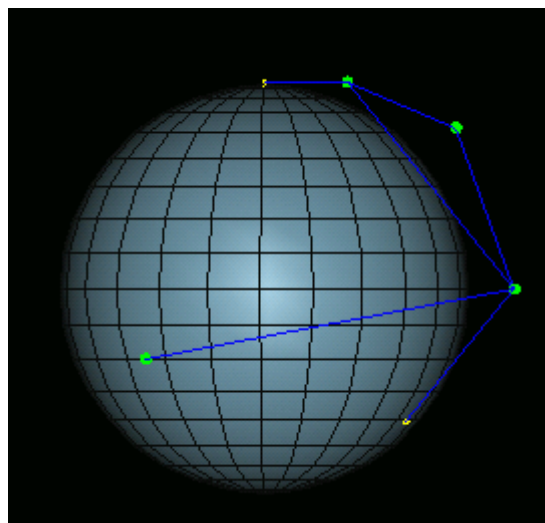


Figure 2. The Server's graphic screen

## 2. SIMULATION OF A CONSTELLATION OF SATELLITES

We have developed our own satellite simulator to illustrate our research ideas outlined in this paper. The simulator follows the principles of TechSat 21 [8]. SaVi is a similar software created at the Geometry Center at the University of Minnesota for the visualization and analysis of satellite constellations [3]. It has been used to simulate various satellite constellations such as Globalstar, Iridium, and Teledesic. SaVi differs from ours in that it is simply a simulator of orbital satellite constellations, and does not implement autonomy in its satellites.

Our simulator is composed of two primary modules; the server, and the agent. The server module handles the creation of all agent objects in the simulation and acts as a router to facilitate the passing of messages between various agents. There are two types of agents that can be created within this environment, satellite agents and ground station agents. These agents are implemented as objects and have similar capabilities, with the satellites having the additional ability to change their location within the environment. The server module is also responsible for the accurate

representation of all objects in the graphical environment (Figure 2).

The agent module contains the functional components of the agents. These components constitute the essence of the agent's purpose and functionality. Behavioral functions and autonomy states can be created and transitioned by accessing these module components through the use of behavior rules in the agent's behavior file. Behavior rules are comprised of conditional checks and assignment calls to the functional components in the form of simple production rules.

The satellite simulator was implemented using Mesa and supported by the collision detection routines which are part of the SOLID library package. The simulation is comprised of a central solid sphere surrounded by a wire-frame sphere to establish a latitude/longitude coordinate system. The sphere is currently scaled to represent the earth, and rotational velocity is approximately 120 times nominal. Graphically, the satellites are represented as green spheres with groundstations being yellow spheres on the planet's surface. The entire simulation can be rotated on any of the three axes. This allows for the simulation to be viewed from various perspectives. Additionally, any agent can be selected to be "tracked" in the simulation. This has the affect of centering the agent at the origin, with all other objects, including the planet, revolving around the agent. Blue line segments are used to show connections between satellites that have a line of sight communications capability, or connections between a satellite and a ground station (Figure 4). The SOLID library was used to make this determination, since the Mesa libraries do not directly support the detection of intersections between the connecting line segments and the planetary bodies. All satellites orbit at velocities which are appropriate for their altitude, with respect to a planet such as the earth.

The satellites and ground stations that orbit and reside on the planet are implemented as objects and have communication capability to other agents via message passing through the socket connection with the server. The position of each of these agents is determined by the data that is provided to the server in a text file. The text file contains only the most basic of information necessary to place the agent in the graphics environment of the server.

As each agent object is created, it reads a behavior file, which contains the rules that will govern its actions with respect to communication policy and physical actions that may be needed to achieve a desired goal. The format and examples of these rules is described in more detail in the next section.

### 3. TAKING 3 SCANS OF AN AREA

Assume the ground station will need three independent images of a given longitude and latitude from a given altitude. Let's call the task 3Image. The ground station issues the command to the nearest satellite and that satellite will be responsible to perform the task either by itself if no satellites are available. The satellite will complete the images itself taking one image in each orbit crossing the given location. If the satellite so decides it recruits other satellites to complete the task. Each of the recruited satellites may recruit another satellite. After recruiting one satellite, either satellite may decide to recruit a third teammate.

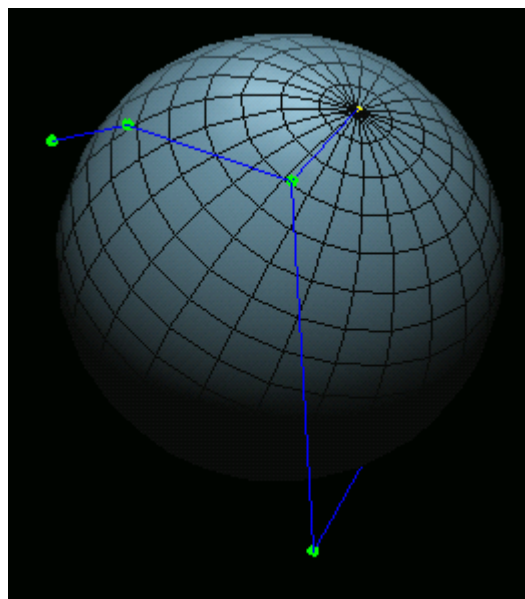


Figure 4. Communication lines

Here we will present a conversational policy that will govern interagent communication.

The following are the agent *speak states*:

- 0 – Start state
- 1 – Ground station has issued a command and a Satellite has received this message.
- 2 – A satellite has received and accepted the command.
- 3 – A second satellite has been contacted.
- 4 – The second satellite has accepted the command.
- 5– A third satellite has been contacted.
- 6– The third satellite has accepted the command and we now have a team.
- 7- Ground control has received the first image.
- 8- Ground control has received the second image.
- 9- Ground control has received the third image.
- 10- Success State

**11-** Failure State. This state occurs when any of the images are not received in a reasonable amount of time. State 0 is the start of 3-imaging.

The following are the set of available *words/phrases*:

- S0** – Satellite agent says “Hello” to other agents to announce its presence, if it is currently idle.
- S1** – Ground station issues a command 3Image [Longitude] [Latitude] [Altitude]
- S2** – A satellite accepts command. The satellite says "Roger to 3Image"
- S3** – Ground states acknowledges that a team leader has agreed to take the task and will now accept images by speaking “Ready to receive images”.
- S4** – A satellite recruits another satellites for 3Image. The satellite may say “Team 3Image?”
- S5** – If a satellite accepts the request for being part of a team for 3Image, it may say “Willco”.
- S6** – If a satellite rejects the request for being part of a team for 3Image, it may say "Unable".
- S7** – “bye” is spoken when a team member is no longer able to be part of the team.
- S8** – “Downloading Image #1” is spoken when image #1 is downloaded to the ground Station.
- S9** – “Downloading Image #2” is spoken when image #2 is downloaded to the ground Station.
- S10** – “Downloading Image #3” is spoken when image #3 is downloaded to the ground Station.
- S11** – “Received Image #1” is spoken when image #1 is received by the ground Station.
- S12** – “Received Image #2” is spoken when image #2 is received by the ground Station.
- S13** - The ground station may say “Task Complete” when all three images are received.
- S14** - With an excessive silence, the policy ends unsuccessfully, “Task Aborted”.

The following are the *physical conditions*. For each condition we note the agent that perceives it.

- P0** – Start condition.
- P1** - There is a need for 3Imgaing and a satellite is chosen for tasking. This condition is perceived by GROUND only.
- P2** - Satellite is unable to participate in a team for one of two reasons: It is in danger or it has not yet finished its previous task. This condition is perceived by the SAT that is contacted to perform the task.
- P3** – Satellite is able to take lead on a task and is available. This condition is perceived by SAT only.
- P4** – Another satellite is detected that can potentially be a team-mate. This condition is perceived by SAT.
- P5** - Satellite is able to be a team-player. This condition is perceived privately by the SAT. All SAT agents privately perceive conditions P6-P10.
- P6**- An image has been collected.

- P7**- An image has been successfully collected and transmitted to the ground station.
- P8**- Two images are successfully collected and transmitted to the ground.
- P9**- Three images are successfully collected and transmitted to the ground.
- P10**– The chosen Satellite has received the command. Ground station is now ready to receive images. This condition is perceived by GROUND only.
- P11**- All the external conditions and instrumentation conditions for taking a picture are met.

In the following *speak state transitions*, each agent’s type is noted by a “GND” for ground station or “SAT” for satellite. SATAVL, TIMEOUT, UNABLE, AND PICT are boolean conditions. SATAVL determines if a satellite agent is available (free of prior tasks and capable of taking on new a task) for the current agent. The availability is determined with respect to the satellite’s current speak state and physical conditions. TIMEOUT holds if an excessive amount of time has elapsed since the last change in speak state. PICT indicates if the agent has any pictures that can be downloaded to the ground station. UNABLE denotes the satellite’s propioception of being busy with a prior task or somehow being “out of service”. PICT denotes the absence of such a condition. “SPK:<destination>” construct is used to specify to whom the spoken phrase is intended. CUR\_AGNT is the agent most recently identified as available by the SATAVL check. The default CUR\_AGNT is the speaking agent.

The following are the *speak-state transitions*.

- P0\*1\*GND\*S1\*→0
- P3\*0\*SAT\*S1→1
- P3\*1\*SAT\*S3→2
- P4\*2\*SAT\*S4→3
- P4\*4\*SAT\*S4→5
- P4\*3\*SAT\*S6→2
- P4\*3\*SAT\*S4→4
- P4\*5\*SAT\*S5→6
- P5\*0\*SAT\*S3→2
- P2\*3\*SAT\*S7→0
- P2\*4\*SAT\*S7→0
- P2\*5\*SAT\*S7→0
- P2\*6\*SAT\*S7→0
- P2\*7\*SAT\*S7→0
- P2\*8\*SAT\*S7→0
- P4\*4\*SAT\*S7→2
- P4\*5\*SAT\*S7→3
- P4\*6\*SAT\*S7→4
- P7\*2\*SAT\*S11→7
- P7\*4\*SAT\*S11→7
- P7\*6\*SAT\*S11→7
- P6\*2\*SAT\*S11→7
- P6\*4\*SAT\*S11→7
- P6\*6\*SAT\*S11→7
- P8\*7\*SAT\*S12→8

P6\*7\*SAT\*S12→8  
 P7\*7\*SAT\*S12→8  
 P9\*8\*SAT\*S13→9  
 P6\*8\*SAT\*S13→9  
 P7\*8\*SAT\*S13→9  
 P8\*8\*SAT\*S13→9  
 P10\*0\*GND\*S2→1  
 P10\*1\*GND\*S3→2  
 P10\*2\*GND\*S8→7  
 P10\*7\*GND\*S9→8  
 P10\*8\*GND\*S10→9  
 P10\*9\*GND\*S13→10  
 1\*SAT\*S14→11  
 2\*SAT\*S14→11  
 3\*SAT\*S14→11  
 4\*SAT\*S14→11  
 5\*SAT\*S14→11  
 6\*SAT\*S14→11  
 7\*SAT\*S14→11  
 8\*SAT\*S14→11  
 P10\*1\*GND\*TIMEOUT→11  
 P10\*7\*GND\*TIMEOUT→11  
 P10\*8\*GND\*TIMEOUT→11

The following are the *speech transitions*. SA denotes the agent's level of situated autonomy.

P0\*0\*SAT\*TIMEOUT→SPK:ALL\*S0  
 P1\*0\*GND\*TIMEOUT→SPK:CUR\_AGNT\*S1  
 P0\*0\*SAT\*S4→P5  
 P3\*1\*SAT→SPK:ALL\*S2  
 P10\*1\*GND→SPK:ALL\*S3  
 P4\*2\*SAT\*SA→SPK:ALL\*S4  
 P5\*0\*SAT\*S4→P2  
 P6\*2\*SAT\*SA→SPK:ALL\*S5  
 P7\*2\*SAT\*SA→SPK:ALL\*S8  
 P4\*4\*SAT\*SA→SPK:ALL\*S4  
 P2\*4\*SAT\*SA→SPK:ALL\*S7  
 P7\*4\*SAT\*SA→SPK:ALL\*S8  
 P2\*6\*SAT\*SA→SPK:ALL\*S7  
 P7\*6\*SAT\*SA→SPK:ALL\*S8  
 P2\*0\*SAT→SPK:ALL\*S6  
 P2\*3\*SAT→SPK:ALL\*S7  
 P2\*5\*SAT→SPK:ALL\*S7  
 P2\*7\*SAT→SPK:ALL\*S7  
 P2\*8\*SAT→SPK:ALL\*S7  
 P8\*7\*SAT→SPK:ALL\*S9  
 P9\*8\*SAT→SPK:ALL\*S10  
 P10\*7\*GND→SPK:ALL\*S11  
 P10\*8\*GND→SPK:ALL\*S12  
 P10\*9\*GND→SPK:ALL\*S13  
 P10\*11\*GND→SPK:ALL\*S14

The following are the *act transitions*. "A" denotes an act, which in 3Imaging is taking a picture.

P11\*2\*SAT\*SA→A  
 P11\*4\*SAT\*SA→A  
 P11\*6\*SAT\*SA→A

In addition to the conversational policy and action rules (above), we have designed rules for our agents to infer physical conditions based on exiting physical conditions and their current speak states and either (a) what they hear, (b) proprioception of time or success of their own task (taking a picture), or (c) perception (availability of another satellite for teaming). We will consider these rules to be more domain oriented and intended for internal use of agents. Collectively, we will refer to these rules as domain rules.

The following are mainly based on hearing.

P1\*0\*GND\*S2→P10  
 P2\*0\*SAT\*S7→P0  
 P0\*0\*SAT\*S1→P3  
 P4\*4\*SAT\*S5→P3  
 P0\*0\*SAT\*S3→P5

The following are mainly based on agent perception.

P0\*0\*GND\*SATAVL→P1  
 P3\*2\*SAT\*SATAVL→P4  
 P3\*4\*SAT\*SATAVL→P4

The following are mainly based on agent proprioception.

P1\*1\*GND\*S1\*TIMEOUT→P0  
 P5\*2\*SAT\*PICT→P6  
 P4\*6\*SAT\*PICT→P6  
 P4\*6\*SAT\*PICT→P7  
 P6\*2\*SAT\*PICT→P7  
 P6\*4\*SAT\*PICT→P7  
 P6\*7\*SAT\*PICT→P8  
 P7\*7\*SAT\*PICT→P8  
 P6\*8\*SAT\*PICT→P9  
 P7\*8\*SAT\*PICT→P9  
 P8\*8\*SAT\*PICT→P9  
 UNABLE→P2

#### 4. USING CONVERSATIONAL POLICY

Agents can use the conversational policy for forming their beliefs, goals, and intentions. Each agent will apply the policy, action, and domain rules to new messages it receives. The following is our highest-level loop pseudo code for agent update.

```

For (agent; 1; numAgents)
  While (new receive message)
  {
    1. Determine SA
    2. For (rule; 1; numRules)
      If (rule applies)
        a. Perform transitions
           Use SA to resolve conflicts
        b. Update beliefs and goals
    3. Perform the intention for speaking or acting
       within reaction constant
  }
    
```

Given a goal and the prevailing physical conditions agents constantly update their SA. SA is used in resolving conflicts in rules and in final decision of intention to be formed. Based on situated autonomy agents perform their picture taking or recruit other agents as teammates. The GND agent will note P0 or P1 (and form a belief) and will instantiate an instance of 3Imaging conversational policy. GND will maintain state 0 as its goal. Being in state 0 and having perceived P1, GND will use a speak transition to intend and then to issue S1. If the satellite (call it SAT1) has received the message S1 the speak state transition is used to reach state 1. GND and satellite SAT1 share the goal of being in state 1. SAT1 may perceive P3 and using a speak state transition to arrive at a desire to be in state 2 and also form an internal goal in achieving the command. GND does not determine P3 so it has no access to this perception. It however has access to the state transition that allows it to desire state 2. In state 2, SAT1 privately considers P3, P4, and P11 and arrives at a determination of situated autonomy. In 3Imaging, the lead agent once it reaches state 2, must consider exogenous physical conditions 3, 4, and 11 along with all agent endogenous factors to determine its autonomy. If it decides on shared autonomy, the agent must begin recruiting other agents as teammates. Otherwise, it will either do the task itself or delegate it to others.

If SAT1's decision favors a team formation, it uses a state transition to arrive at state 3 and forms a desire in it. Due to space limitation, we will not discuss the details of team formation. Since P4 is not shared with GND, it does not have the same belief. Let's call the second Satellite SAT2. SAT1 and SAT2 now share the desire to be in state 3. If SAT2 perceives P5, it will use a state transition and moves to state 4 and forms a desire in state 4 and the goal to be a teammate in 3Imaging. If SAT2 perceives P2, it will inform SAT1 and move back to state 2. SAT2 no longer has to want state 3. SAT1 will desire State 2.

For an agent that is recruited to be a teammate in state 4 it has already decided to have shared autonomy. It must consider its exogenous physical conditions 3 and 4 (P3 and P4) along with all agent endogenous factors to determine its autonomy in order to decide whether yet another teammate is needed. If it decides to recruit another agent it will move through states to state 6.

For an agent that is recruited to be a teammate in state 6 it has already agreed to have shared autonomy and since it is the third member of the team no other teammates are needed. Conditions P6-P9 may be perceived by either Satellite agent and all SAT agents share goals in state 7-11.

In the next section we will briefly discuss how autonomy will vary.

## 5. AUTONOMY MEASURES

Situated Autonomy depends on time, and strengths of belief and goal. [6]. Each agent reacts at different speeds. The times between sensing and acting is an agent's reaction constant and the optimal values can be learned. This greatly affects the agent's autonomy decision. Temporally, from the shortest reaction time to the longest, an agent's autonomy is based on its pre-disposition, disposition, and motivation. Therefore, an agent's reaction constant is important. An agent's beliefs used in autonomy decision vary from weak to strong. An agent's goals are directed to self, other, or group. The goals vary in strength of motivation from weak to strong.

In 3Imaging, agents have different reaction constants and we are experimenting with the effect of slow versus fast reacting satellites. An agent's beliefs are about the physical conditions and the speak states and change in strength. The goals are about taking images and they vary based on the agent's prior commitment. If a Satellite agent has committed to a 3Imaging task, it might commit to yet another 3Imaging command if it senses that it can complete the task. After the first command, the motivation level for the goal is set to be less than for the first command. A combination of belief and goal degrees are used for determining SA.

As of this writing, our implemented system runs and images are gathered. However, we do not yet have situated autonomy experiments. We plan to compare runs of the system with different reaction constants. The autonomy levels in our agents will be learned as combinations of beliefs and goals. The metrics we will use for feedback are timeliness of images collected.

## 6. SUMMARY AND CONCLUSION

We have developed a production-style representational framework that unifies acting and speaking. Our representation extends conversational policy scheme. It explains how agents can use the shared normative models of conversational policy for forming private beliefs, goals, and intentions. We outlined a scheme for flexible teaming that uses the notion of situated autonomy.

We have implemented our model in the domain of constellation of satellites. Our system runs but we have not yet completed experiments with how timely team formation improves our system performance.

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