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ACQUISITION DECISION SUPPORT WITH MONTEREY PHOENIX

by

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ABSTRACT

The number of possibilities that can arise from complex system behaviors and interactions is regularly underestimated by approaches and tools that are biased towards the capture of known and wanted behaviors. This research tests a new methodology for exposing and controlling unknown and unwanted behaviors using Monterey Phoenix models, and then assesses risk of events and event traces as an example analysis that informs acquisition decisions. A summer internship activity was conducted to guide the development of source data for this research based on behavior models of a competition known as Aquaticus. The new emergent behavior analysis methodology is applied to provide a set of validated scenarios to inform risk analysis. An initial model contained two traces showing unexpected game rule violations, which were corrected in a final model containing eight traces of valid potential behavior possibilities for the blue team, red team, and environment. Risk factors were then computed for each trace to inform overall risk statistics across the entire model, including a total risk (sum of all trace risk factors), a maximum risk, and an average risk across all eight traces. This methodology provides the first rigorous and systematic search pattern for 'unknown unknown' behaviors supported by automated tools. It increases awareness and understanding of emergent behaviors within and among systems and the environment.

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List of Acronyms and Abbreviations

NPS	Naval Postgraduate School
NRP	Naval Research Program
MP	Monterey Phoenix
NSA	National Security Agency
NCS	National Cryptologic School
MPVIP	Monterey Phoenix Virtual Internship Program
USMA	United States Military Academy
MDO-HuRT-S	Multi-Domain Human-Robot Teaming Sandbox
MOOS-IvP	Mission Oriented Operating Suite - Interval Programming
SAR	Search and Rescue
DOD	Department of Defense
EBA	Emergent Behavior Analysis
MIT	Massachusetts Institute of Technology
MARFORCYBER	United States Marine Corps Forces Cyberspace Command
VA	United States Department of Veterans Affairs
ASPIRE	All Services Personnel and Institutional Readiness Engine

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CHAPTER 1:
Introduction

This research applies the Monterey Phoenix (MP) approach and tool for behavior modeling to a force-on-force competition model to test a methodology for exposing unwanted emergent behaviors that were previously unknown from synthetically generated sets of scenarios. The project goal is to advance acquisition decision making approaches by using more complete sets of event traces. The project found four unwanted emergent behaviors in the competition model and also a model of competency assessment, created a state diagram from the competition model, and completed a risk analysis using the competition model as one example application of acquisition decision making tools. The emergent behavior analysis capability being tested in this research is directly applicable to the topic sponsor's mission to develop and supervise plans, policies and strategy for operating in the information environment, and to identify related requirements in doctrine, manpower, training, education, and equipment. The Aquaticus force-on-force model used in this research contains behaviors that are similar or analogous to behaviors found in an information environment. This project benefits organizations that need to find unwanted behaviors before they occur in deployed systems to reduce program risk and risk to operators in the Fleet.

1.1 Background

Monterey Phoenix [1] [2] is an NPS-created language, approach, and tool that assists its user to formally model and reason about behavior – the way in which something (e.g., a system, software, hardware, person, process) conducts activity. As a "lightweight" [3] [4] formal method and framework, it fills a capability gap present in other behavior modeling approaches and languages used by the Navy and other agencies in that it generates the exhaustive set of possible behavior scenarios up to a limited scope for a given model of behavior. It is also distinct from "heavyweight" formal methods in that it does not require a substantial amount of mathematical expertise to generate this exhaustive set of scenarios. Two tools, MP-Firebird [5] and MP-Gryphon [6] were developed at NPS to promote education of formal methods for system behavior modeling and to make Monterey Phoenix a cost-effective option for workforces designing complex systems at risk for exhibiting unwanted emergent behavior. MP-Firebird runs through a user's web browser requiring no installation, with models sent over an internet connection for processing. MP-Gryphon is downloaded and installed on the user's machine and models are processed locally without an internet connection. These tools have been made available to the public without cost or license restrictions to promote the development of safer, more secure, and more resilient systems in all industries and domains of application.

In 2020, a virtual summer program was created and sponsored by the National Security Agency (NSA) National Cryptologic School (NCS) in partnership with NPS. This program piloted the use of MP as a framework for emergent behavior analysis, testing the claim that MP can be used to expose and control unexpected emergent behaviors in systems. The participants discovered eleven unexpected emergent behaviors in systems from different domains leading to ideas for new requirements, and also discovered an identical behavior pattern in two very different systems (an isomorphism). Given its success in 2020 as an outreach tool that had a valuable impact on real world systems worked on by expert mentors, the internship was given the name Monterey Phoenix Virtual Internship Program (MPVIP) and repeated in 2021. Between these two summers, a total of 104 college student participants, 15 SME mentors, and 10 MP model coaches participated in the MPVIP.

One of the systems in which emergent behavior was discovered by previous MPVIP participants was a set of competition game rules for a project called Aquaticus, which has an environment for human-robot teams to compete with other human-robot teams in a "capture the flag" -inspired game. The Robotics Research Center at the United States Military Academy (USMA), which studies multi-robot teams, perception, and human-robot teaming in challenging environments, rehearses for these competitions at their Multi-Domain Human-Robot Teaming Sandbox (MDO-HuRT-S). The MDO-HuRT-S conducts exercises with ground, surface and air assets programmed with autonomy algorithms by students and researchers. Interns from the second cohort of the MPVIP built a model that generated a scope-complete set of event streams for an Aquaticus force-on-force competition, and interns from the third cohort added halt-competition events involving search and rescue (SAR) emergency response scenarios. These interns were mentored by Dr. John James, an Associate Professor at the United States Military Academy who is a member of a team of researchers seeking enhanced formalisms for specifying the behavior algorithms controlling the autonomous systems for adherence to commander's intent as the human-robot team executes its mission. As a result of the MPVIP, the MDO-HuRT-S team at West Point is using MP for formal specification of autonomous system behavior algorithms in order to expose and control unexpected and unwanted behavior in advance of live competitions and ultimately real world operational use of autonomous systems.

At the request of the topic sponsor, this NRP research project used the MDO-HuRT-S competition models as a source of unclassified data and an MPVIP in the Summer of 2022 as an analysis framework to accomplish the research objectives described in the next section.

1.2 Research and Analysis Objectives

This research explores the following question: what is the ideal human-machine partnership for exposing and controlling emergent behaviors and discovering undocumented requirements and assumptions? The research employed a five-week virtual format in which DOD-affiliated interns learned the MP language and a methodology for exposing and controlling emergent behaviors. The participants worked under the mentorship of subject matter experts – volunteers from involved agencies – and MP coaches from NPS, to produce system use cases in search of emergent behaviors leading to the discovery of requirements. The five-week program concludes with a showcase presentation to senior leaders and invited guests, at which the participants outbriefed their models and findings.

To answer the research question, we tested the current methodology for emergent behavior analysis (EBA) shown in previous MPVIP events to support discovery of unknown and unwanted behaviors from synthetically generated sets of scenarios. To provide source data for this test, this project conducted a Summer 2022 MPVIP analysis activity with collaborators from NPS, USMA, MIT, NSA and MARFORCYBER with the following objectives:

1. refine intern-authored models of the Aquaticus game rules and autonomy algorithms,
2. advance the description of those algorithms with state diagrams, and
3. conduct a risk analysis for all generated event traces.

Towards these main objectives, the following research questions guided the MPVIP analysis activity:

1. What are the potential blue team, red team, and environment behavior possibilities

for an Aquaticus competition?

2. Which event traces adhere to the Aquaticus rules? Are there any event traces that violate the rules?
3. Which events in the game present a risk to the blue team (with likelihood and impact attributes), and which scenarios carry the largest and smallest risks?

1.3 Emergent Behavior Analysis Methodology

Four steps are applied to expose and control emergent behaviors: detection, prediction, classification and control. *Detection* employs the Monterey Phoenix behavior modeling language, approach, and tool to generate a scope-complete set of behavior scenarios automatically and exhaustively for inspection and query (the behavior "superset" for subsequent shaping). *Prediction* and *classification* use human intellect (knowledge, experience, and critical thinking) to form creative stories for event traces using events explicitly present in the model together with intellectually envisioned “circumstantial events.” These stories frequently enable identification of behaviors that are unwanted (negative) and/or unexpected (not previously realized as a design consequence). The scope-complete set of behavior scenarios provides a substantial data source for the analyst to find and control many variants of acceptable or unwanted and expected or unexpected behaviors. To *control* behaviors, the behavior logic is modified or constraints are systematically added to remove unwanted or negative behaviors and leave behind behaviors considered neutral or positive. Validated constraints become formal requirements.

1.4 Report Outline

Chapter 1 introduced the project background, research analysis objectives, and the emergent behavior analysis methodology being tested. Chapter 2 details and refines the work of the Summer 2022 MPVIP interns and maps relevant portions of it to the EBA methodology (research objective 1). Chapter 3 advances the description of game rules and autonomy algorithms described in Chapter 2 using a state machine modeling approach (research objective 2). Chapter 4 conducts a risk analysis for all generated event traces for the Aquaticus SAR Expansion model (research objective 3). Finally, Chapter 5 summarizes the research findings and next steps.

CHAPTER 2: Validation of the Emergent Behavior Analysis Methodology

This chapter presents the Aquaticus model developed by USMA and MPVIP interns and expanded to include procedures for SAR, and also a model of Competency Assessment developed by a separate team of VA and MPVIP interns. It discusses the models and unexpected behaviors discovered by the interns through the lens of the EBA methodology described in the previous chapter as an independent validation of the methodology. Note that the interns were not given the methodology as a step-by-step procedure to follow, but were taught how to look for stories of unexpected behaviors in the traces. All of the compiled findings pertaining to this chapter [7] [8] were presented to leadership from NPS, USMA, MIT, NSA, and MARFORCYBER on the last day of the internship. The following subsections discuss unexpected behaviors found by the SAR Expansion team.

2.1 SAR Expansion (1st Part)

The SAR Expansion team members had started with general knowledge of the Aquaticus game as well as a baseline from the previous year (the Summer 2021 MPVIP). With this information, the SAR team created an MP model with 5 roots, symbolizing the 5 relevant actors present during game play. Upon inspection of the least-restricted model, Trace 3 was chosen for analysis. This is shown in Figure 2.1.

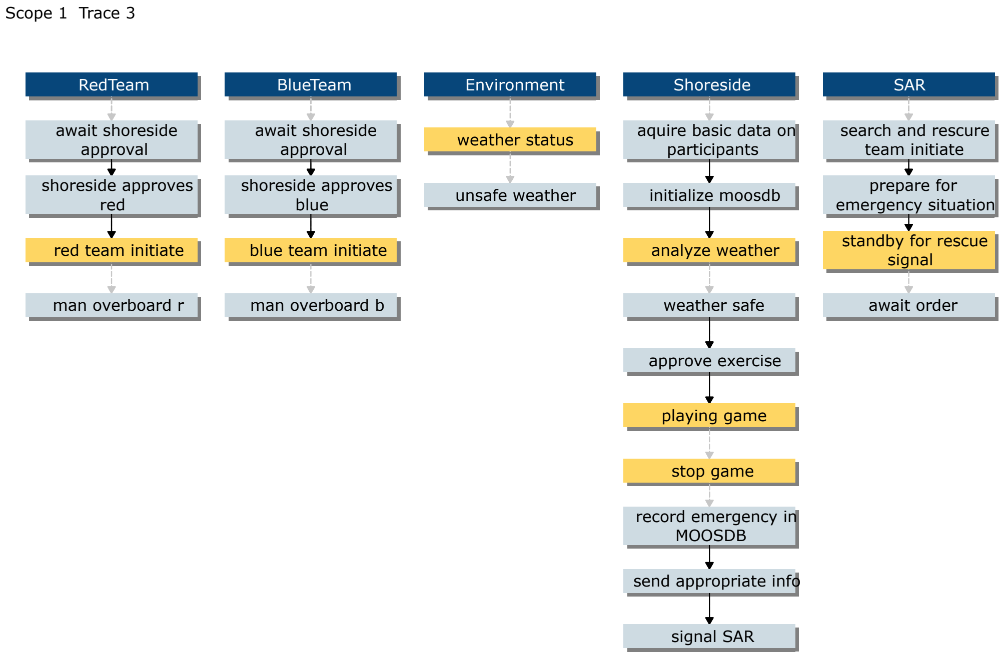

Figure 2.1. SAR Expansion of Aquaticus model - no interactions (Trace 3). Source: [9].

Taking this version with no interactions, two rules known in the game were added: 1) when there are man overboard event(s), Shoreside is made aware and stops the game, and 2) when Shoreside approves the exercise, both Red and Blue Teams are made aware that it has been approved. The updated Trace 3 with the first rule added in can be found in Figure 2.2.

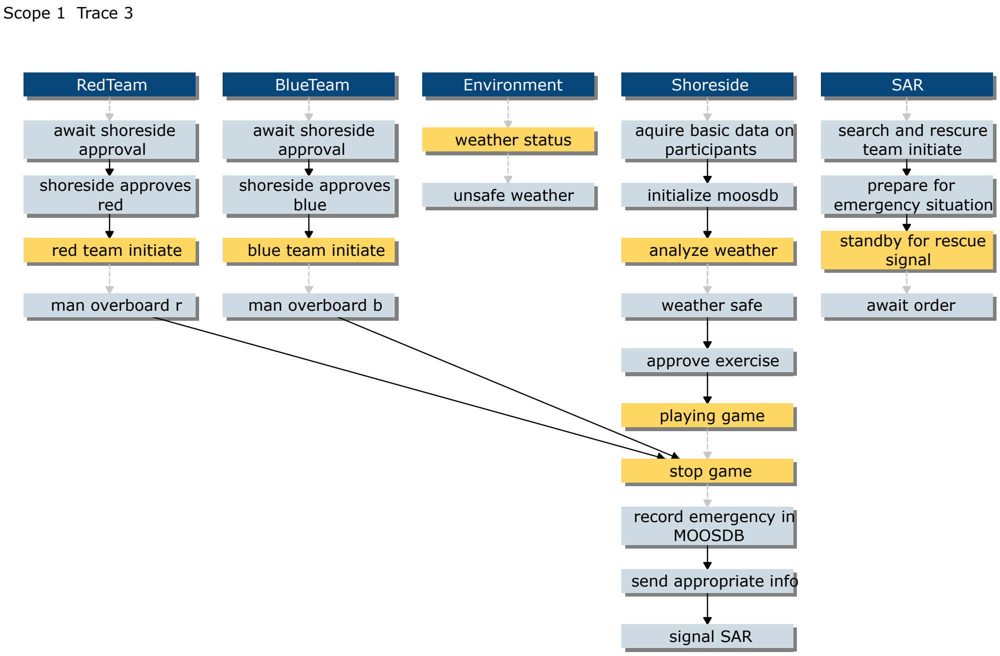

Figure 2.2. SAR Expansion of Aquaticus model - first interaction (Trace 3). Source: [9].

After the second rule was added, Trace 3 was re-inspected, and this version can be seen in Figure 2.3.

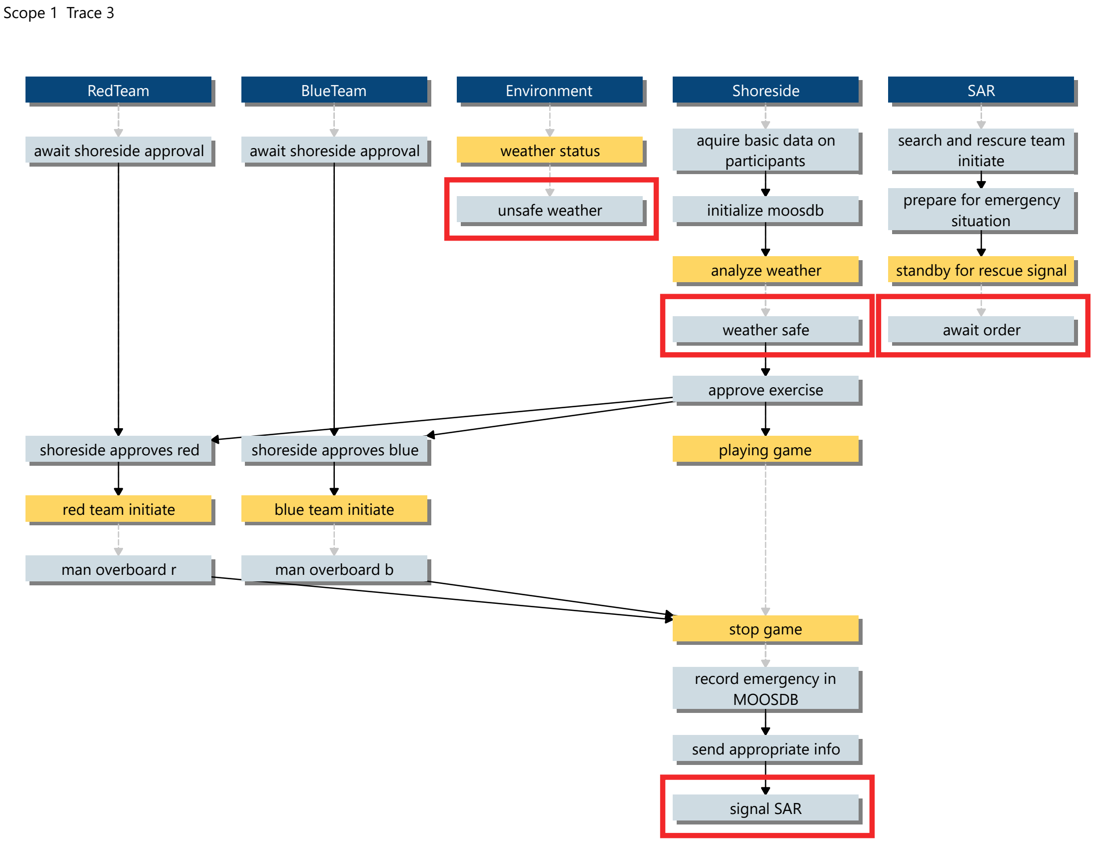

Figure 2.3. SAR Expansion of Aquaticus model - Emergent Behavior (Trace 3). Source: [9].

Multiple violations of game play expectations were detected here, and the example story is as follows: The weather is unsafe but Shoreside believes it is safe, so the game is approved to begin. While it is being played, suddenly a player on the Red Team crashes into a player on the Blue Team, resulting in two man overboard events. SAR is then signaled but the method of communication fails and SAR does not receive the signal at all. SAR remains in the position where it is awaiting an order, unaware that the signal was sent. In Figure 2.3, as just shown, the emergent behavior is classified as strong negative. In fact, this exemplifies compound negative emergence because the game was: 1) played under possibly unsafe conditions, and 2) the man overboards were not rescued in the emergency situation.

The SAR Expansion team member participants from the USMA controlled the first part of the unwanted, unexpected emergent behavior by adding two coordinate statements that assured the environmental weather status matched the Shoreside weather determination in all cases. The discovered requirement for this was that Shoreside should double check the weather conditions before approving the exercise. Below, Figure 2.4 shows this modification, produced from the updated model as Trace 1 with the new weather requirement added in.

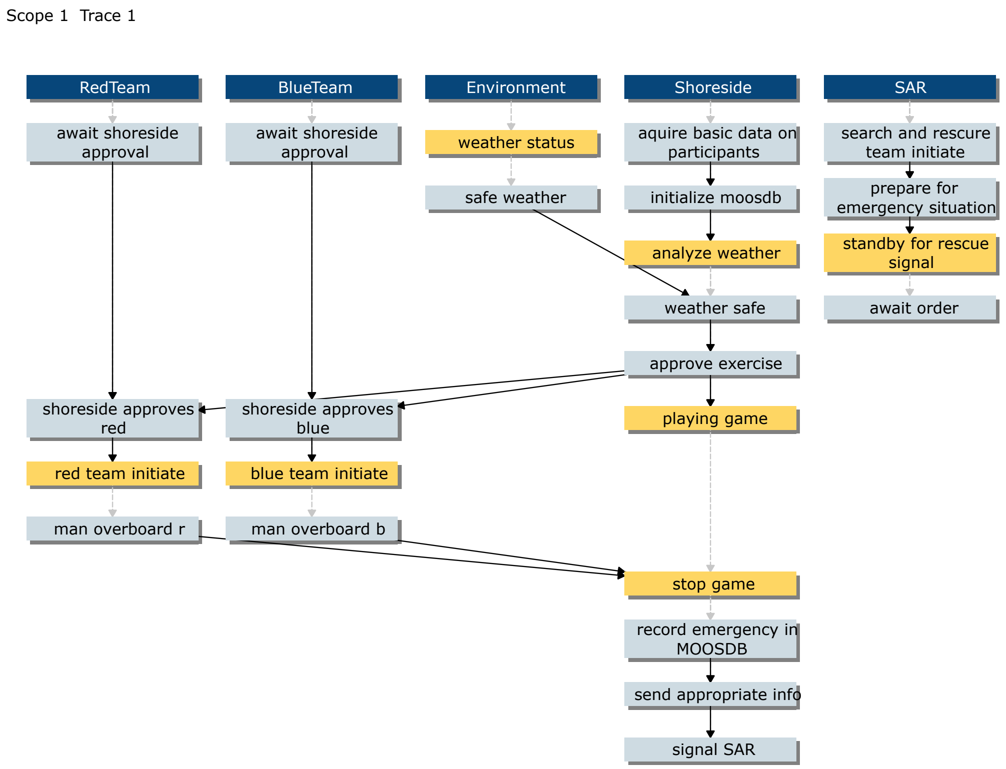

Figure 2.4. SAR Expansion of Aquaticus model - partially constrained (Trace 1). Source: [9].

Then, the participants controlled the second part of the unwanted emergent behavior by adding a final coordinate statement that assured the signal sent from Shoreside was received by SAR in all cases. The discovered requirement here was that Shoreside should check that the signal it sends is always received by SAR. The final controlled result for this emergent behavior (Trace 1) is shown below in Figure 2.5.

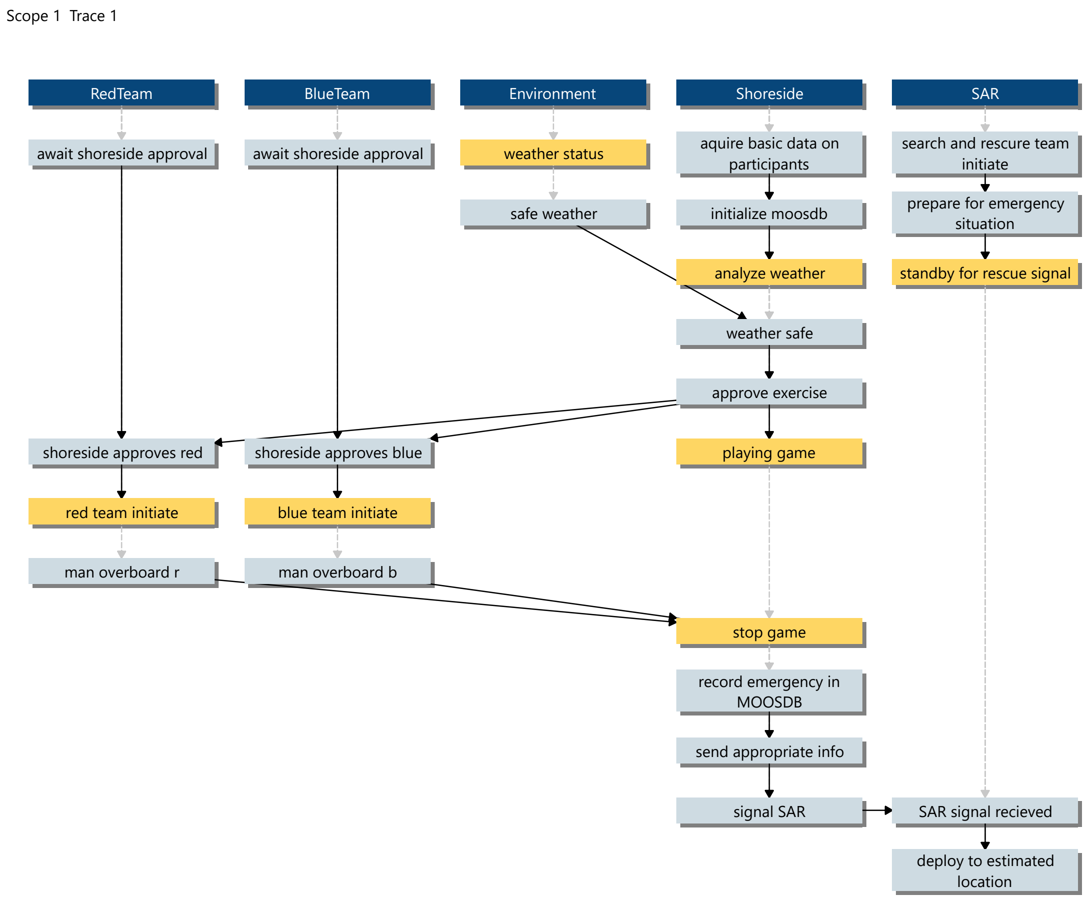

Figure 2.5. SAR Expansion of Aquaticus model - after constraints finalized - Controlled (Trace 1). Source: [9].

2.2 SAR Expansion (2nd Part)

The SAR Expansion participants from the USMA detected a second example of emergent behavior (Trace 30), which is shown in Figure 2.6.

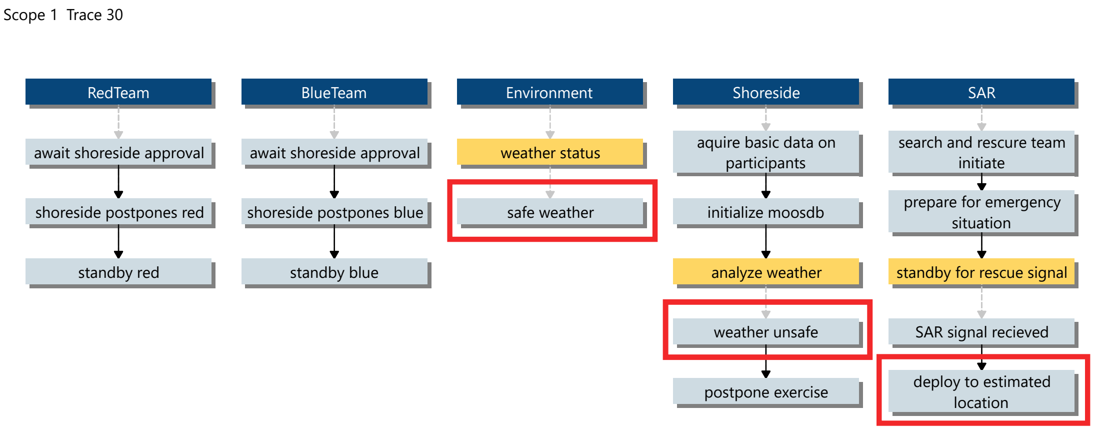

Figure 2.6. SAR Expansion of Aquaticus model - Emergent Behavior (Trace 30). Source: [9].

The example story is: the weather is safe but a possible insider threat occurs, with Shoreside being told the weather is unsafe and the game should be postponed. Even though the game is not played, SAR is deployed due to an "emergency" signal from this insider threat, whose goal is to disrupt game play and consume resources. This emergent behavior can be classified as strong negative. The participants controlled this emergent behavior by adding constraints (coordinate statements) to guarantee Shoreside itself makes the proper determination about the weather, and also that Shoreside and SAR always communicate correctly. For example, unwanted behavior in another game (without these control strategies added) could have been Shoreside signaling SAR for an emergency, but SAR not responding. The final controlled result for this emergent behavior, which became Trace 8 with the new constraints added in, is shown below in Figure 2.7.

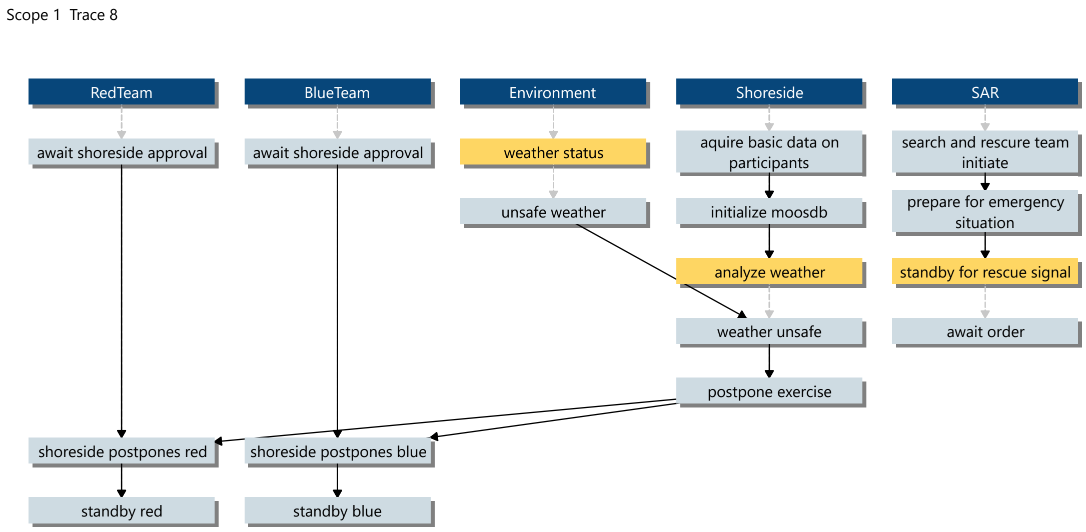

Figure 2.7. SAR Expansion of Aquaticus model - after constraints finalized - Controlled (Trace 8). Source: [9].

2.3 SAR Expansion (3rd Part)

The SAR Expansion participants from the USMA detected a third example of emergent behavior (Trace 2), which is shown in Figure 2.8.

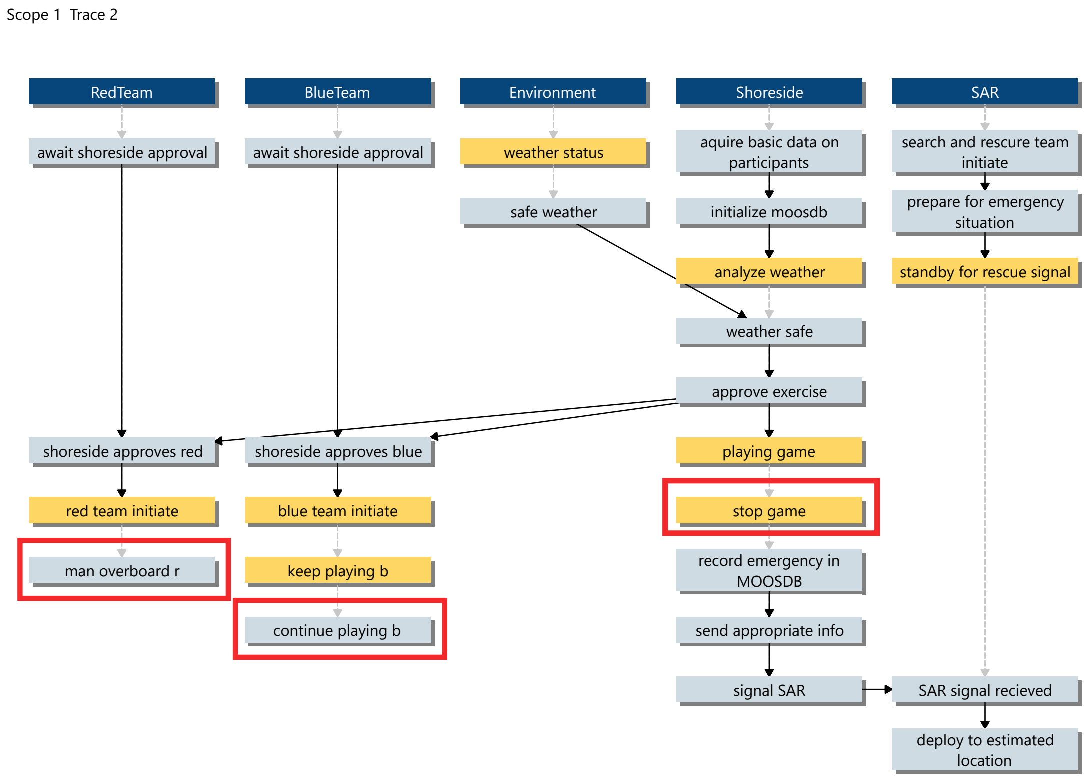

Figure 2.8. SAR Expansion of Aquaticus model - Emergent Behavior (Trace 2). Source: [9].

The example story is: there is a man overboard on one team (here the red) but the opposing team continues playing (here the blue), because they are too focused on the game and unaware that the red team has an emergency situation and SAR is being deployed. This emergent behavior can be classified as strong negative. The participants controlled this violation of game rules by adding a constraint (a conditional coordinate) that required: 1) the opposing team to stop playing if there is a man overboard event, and 2) “stop game” to be properly coordinated with the man overboard event. The final controlled result for this emergent behavior (Trace 2) is shown below in Figure 2.9.

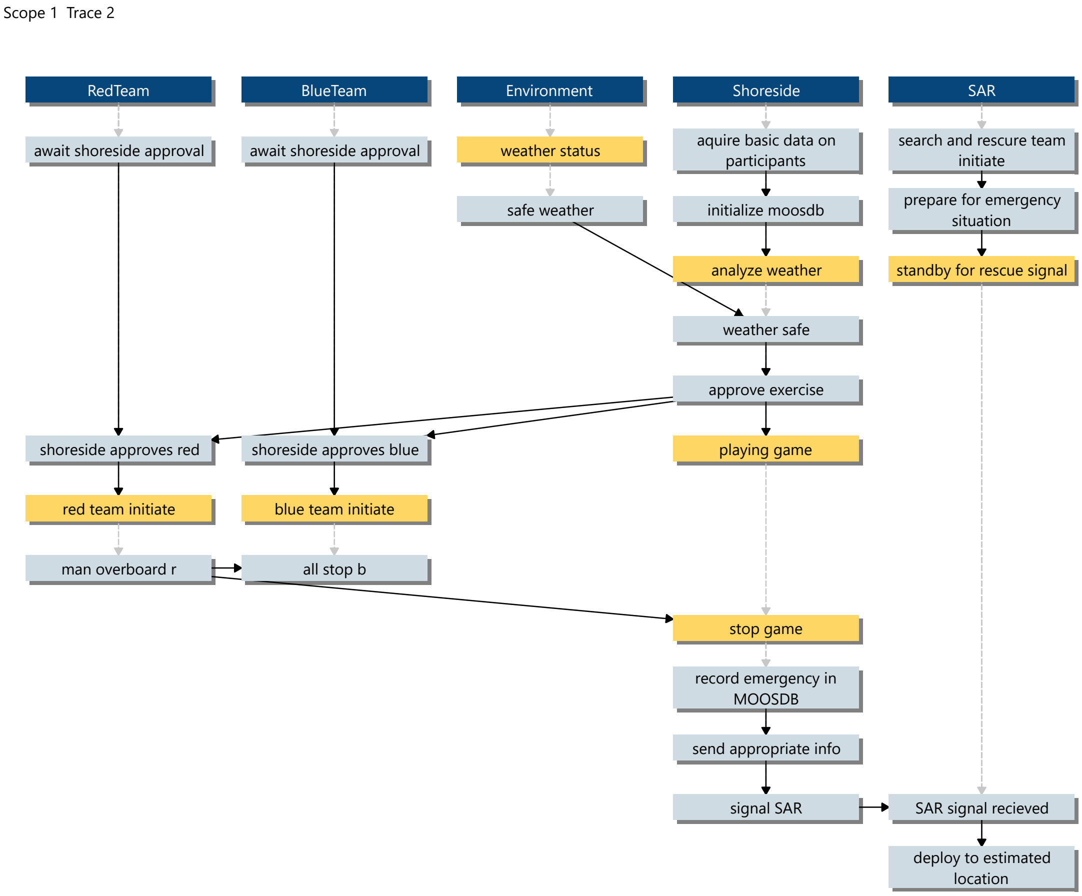

Figure 2.9. SAR Expansion of Aquaticus model - after constraints finalized - Controlled (Trace 2). Source: [9].

To conclude the discussion on the SAR Expansion model, it is informative to show the trace in the final model that symbolizes the baseline case narrative for the Aquaticus game. This Trace 5 is shown below in Figure 2.10, and is the scenario that demonstrates everything occurring as expected in a "normal" game with no emergencies.

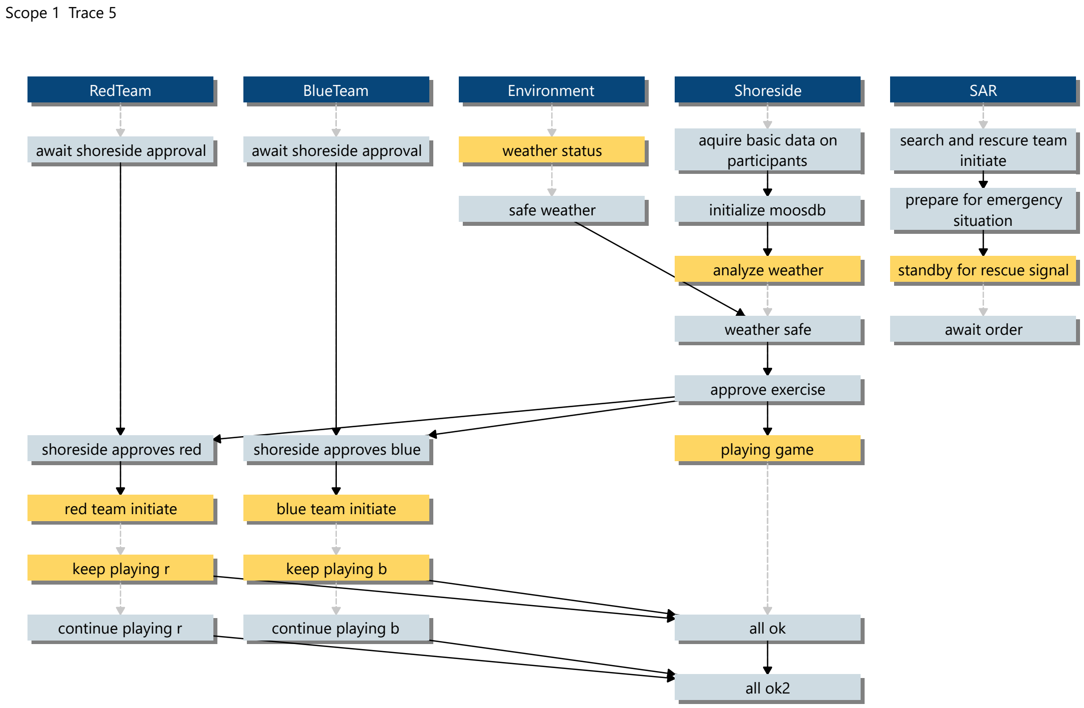

Figure 2.10. SAR Expansion of Aquaticus model - Baseline Case Narrative - safe weather, both teams play as expected, no emergencies, and SAR not needed (Trace 5). Source: [9].

2.4 Competency Assessment

In addition to the SAR Expansion team, there were two participants from the United States Department of Veterans Affairs (VA) in the Summer 2022 MPVIP. The EBA methodology described in Chapter 1 was also validated using results found by this team. These Competency Assessment participants presented [8] all compiled findings to leadership from NPS and the VA, on the last day of the internship. The team created an MP model using general knowledge of the All Services Personnel and Institutional Readiness Engine (ASPIRE) system, and detected the example of emergent behavior (Trace 2) shown in Figure 2.11.

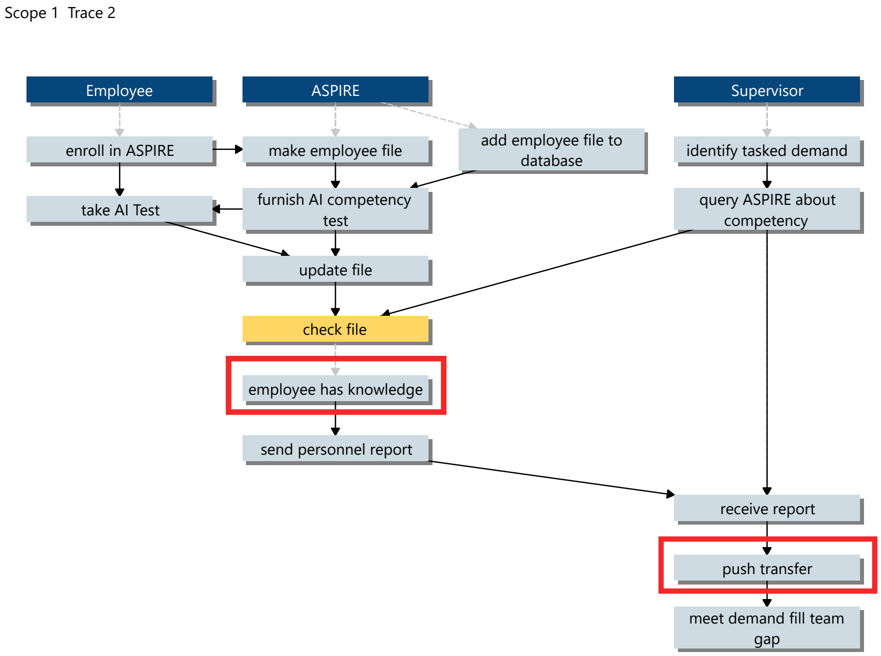

Figure 2.11. Competency Assessment model - Emergent Behavior. Source: [10].

It was predicted that if an employee has the competency but the supervisor still pushes a transfer, this is an exception case. The emergent behavior from the Competency Assessment model can be classified as weak negative. The participants controlled the exception case by adding a constraint (an ensure condition) that required “push transfer” to be an option ONLY when “outside employee has knowledge” was true. The final controlled result for this emergent behavior (Trace 1) is shown below in Figure 2.12.

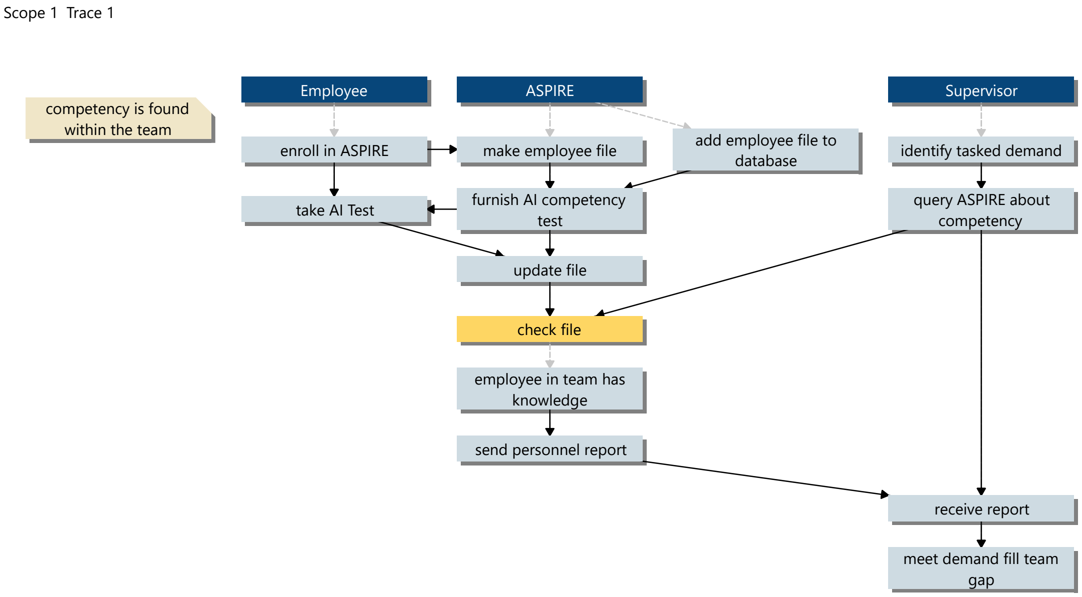

Figure 2.12. Competency Assessment model - after constraints finalized - Controlled. Source: [10].

In Figure 2.13 below, Trace 2 of the Competency Assessment final model shows the typical event flow for when competency is found in an employee outside the team, instead of within the team.

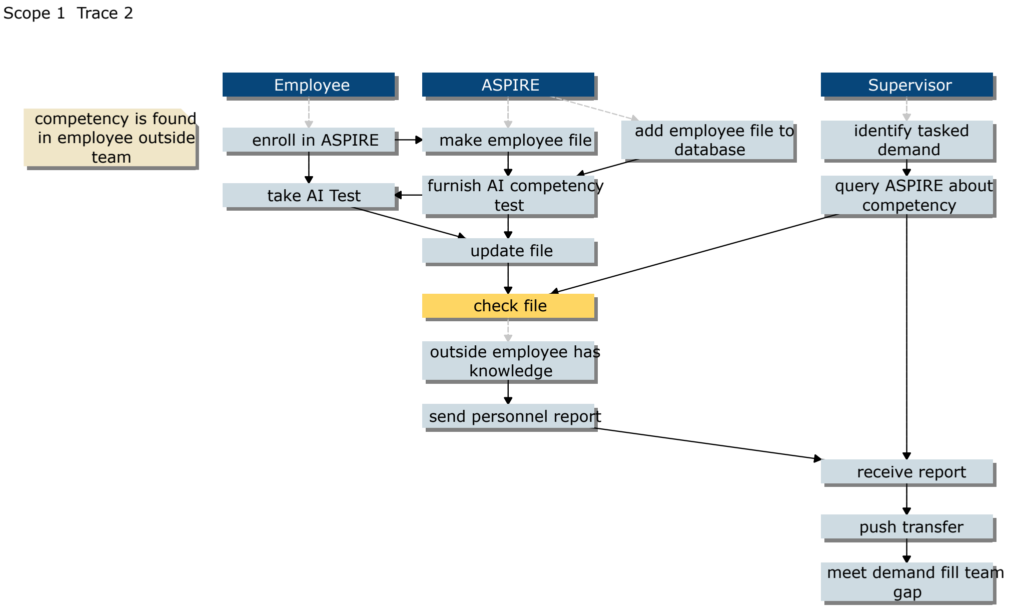

Figure 2.13. Competency Assessment model - competency found outside team. Source: [10].

In Figure 2.14 below, Trace 3 of the Competency Assessment final model shows the typical event flow for when no competency is found on the current team or in an outside employee. This therefore prompts the need for upskilling through ASPIRE.

Scope 1 Trace 3

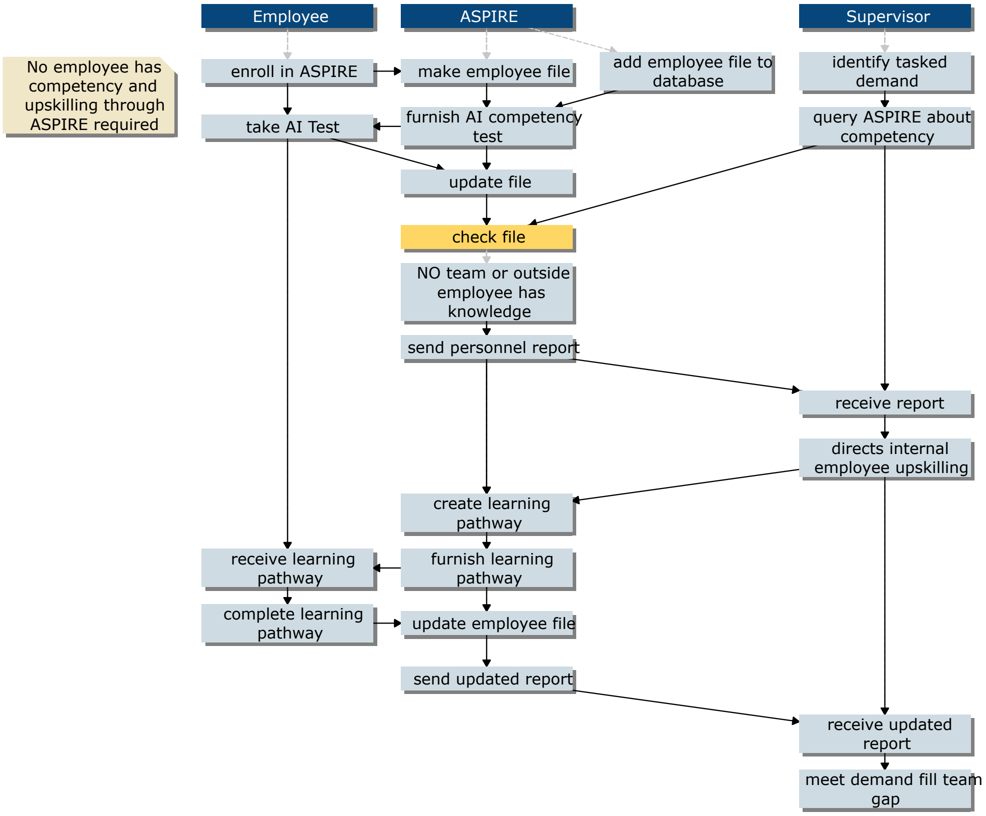

Figure 2.14. Competency Assessment model - upskilling through ASPIRE required because no employee with competency found. Source: [10].

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CHAPTER 3:
State Machine Diagram

In addition to the SAR Expansion and Competency Assessment teams, there was one other MPVIP participant from the USMA who contributed a model relevant to this research. This member was tasked with constructing a State Machine Diagram in MP on the topic of the Aquaticus game, and presented [11] all compiled findings to leadership from NPS, USMA, MIT, NSA, and MARFORCYBER on the last day of the internship. This participant from the USMA created an MP model demonstrating all the detailed steps that the Red Team could follow in the actual game of Aquaticus. This model contained all information needed to capture the full exercise, starting with the robots powering on, to then executing the mission (game) with optional pause and reset sequences, to finishing with the robots powering off. Figure 3.1 below shows the typical event flow for what was determined to be the baseline case narrative from this model (Trace 1): the Red Team robots power on, receive approval for the mission, initialize, then execute the mission, receive the signal to dock once the mission is complete, then dock, and finally power off.

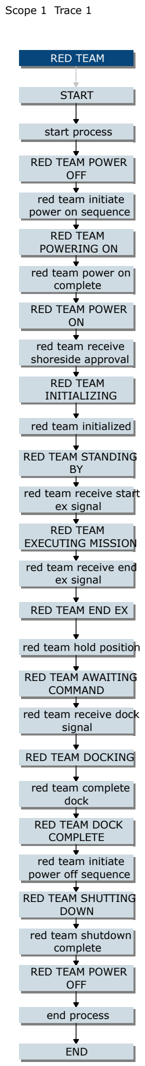

Figure 3.1. Baseline Case Narrative and Typical Event Flow from the State Machine MP model of Aquaticus. Source: [12].

Figure 3.2 below shows the event flow for a different trace from this MP model, which is an alternative case narrative (Trace 5). In addition to the steps from the baseline case shown in Figure 3.1, this trace shows:

1) The Red Team pausing the execution of the mission, holding, and then resuming it again.

The example story for this could be that there was an observed unsafe condition or robot malfunction out in the water, Shoreside sent out the appropriate assistance, the situation was then resolved, so the mission was approved to resume.

2) When the first game is over, the Red Team receives a reset signal and a second game is played. After that is finished, the robots then go through the normal docking and powering off steps.

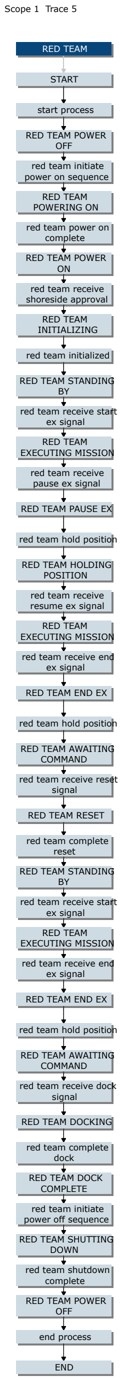

Figure 3.2. Alternative Case Narrative and Event Flow from State Machine MP model of Aquaticus. Source: [12].

Using MP's notation for constructing state machine diagrams, the appropriate categories were completed and added into the model. It is important to note that the names of all "state" events were capitalized, and the names of all "transition" events were given all lowercase letters. This was to make it very clear that events in this model always alternate back and forth between states and transitions, with no exceptions. Running the model in MP with the state machine additions incorporated into it produced the diagram for the Red Team that can be seen in Figure 3.3. All of the unique paths that the Red Team could follow throughout the Aquaticus game are visible in the diagram. It is extremely beneficial to be able to verify that the state diagram is correct and has full coverage, as well as extract each path through it exhaustively - which is exactly what the traces generated from MP are able to provide to all users.

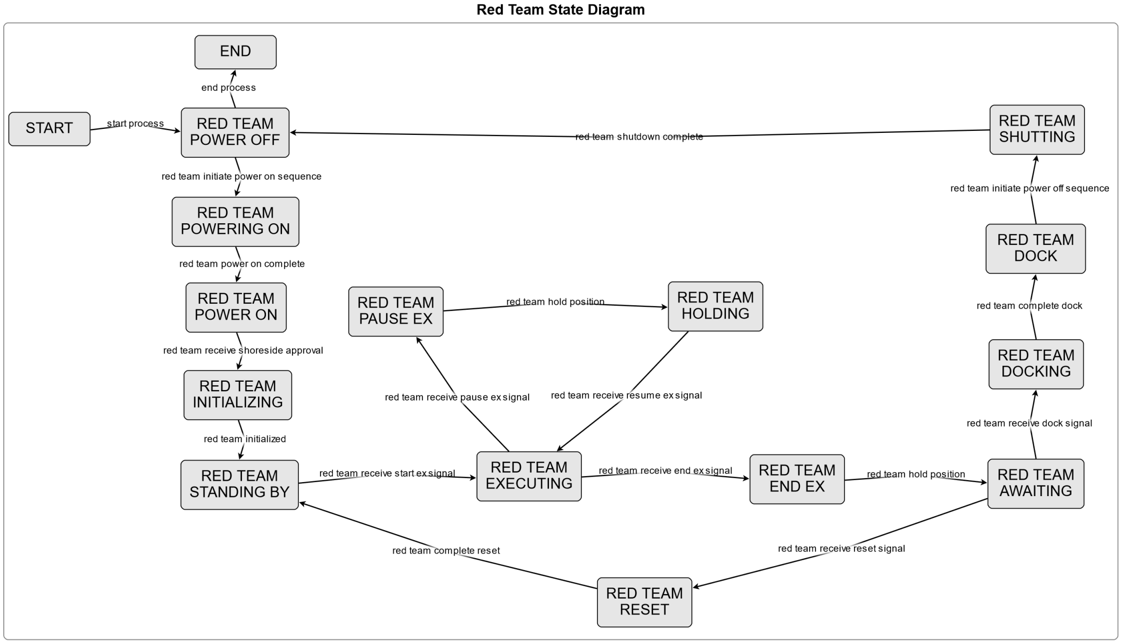

Figure 3.3. State Machine Diagram for the Red Team in the Aquaticus competition (generated from MP). Source: [12].

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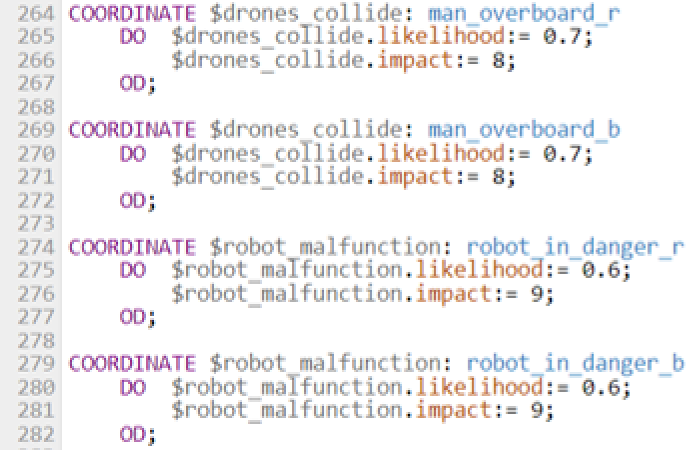
CHAPTER 4:
Acquisition Decision Example - Risk Analysis

Risk analysis is a prominent example of acquisition decision support, and as such was chosen as the example decision support analysis for this research. The same MP model [9] developed by the MPVIP SAR Expansion team [7] was modified to incorporate a risk analysis methodology first developed in 2018 by Moebius [13] and extended in 2021 by Palmieri [14]. Figures 4.1 and 4.2 show the lines of MP code used to assign likelihood and impact attributes to eight events determined to carry risk. The events carrying risk are shown in these figures in a blue font: man overboard events, robot in danger events, unsafe weather events, and continue playing events.



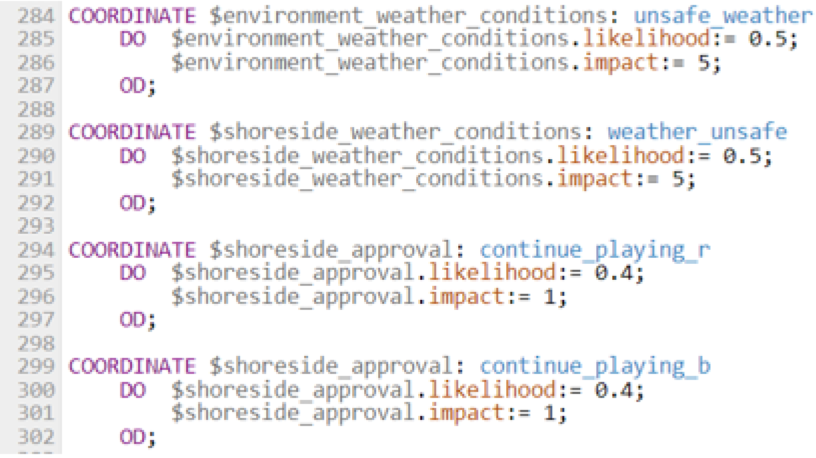
```
COORDINATE $drones_collide: man_overboard_r
    DO  $drones_collide.likelihood:= 0.7;
        $drones_collide.impact:= 8;
    OD;

COORDINATE $drones_collide: man_overboard_b
    DO  $drones_collide.likelihood:= 0.7;
        $drones_collide.impact:= 8;
    OD;

COORDINATE $robot_malfunction: robot_in_danger_r
    DO  $robot_malfunction.likelihood:= 0.6;
        $robot_malfunction.impact:= 9;
    OD;

COORDINATE $robot_malfunction: robot_in_danger_b
    DO  $robot_malfunction.likelihood:= 0.6;
        $robot_malfunction.impact:= 9;
    OD;
```

Figure 4.1. Snippets of code assigning Likelihood and Impact attributes (Part 1). Source: [9].



```
COORDINATE $environment_weather_conditions: unsafe_weather
    DO  $environment_weather_conditions.likelihood:= 0.5;
        $environment_weather_conditions.impact:= 5;
    OD;

COORDINATE $shoreside_weather_conditions: weather_unsafe
    DO  $shoreside_weather_conditions.likelihood:= 0.5;
        $shoreside_weather_conditions.impact:= 5;
    OD;

COORDINATE $shoreside_approval: continue_playing_r
    DO  $shoreside_approval.likelihood:= 0.4;
        $shoreside_approval.impact:= 1;
    OD;

COORDINATE $shoreside_approval: continue_playing_b
    DO  $shoreside_approval.likelihood:= 0.4;
        $shoreside_approval.impact:= 1;
    OD;
```

Figure 4.2. Snippets of code assigning Likelihood and Impact attributes (Part 2). Source: [9].

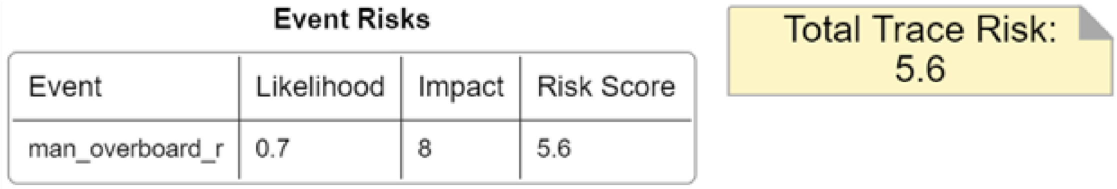
Next, code was written to generate a table that would place events in each trace with nonzero attribute values into rows, and calculate a risk score for each event as well as a total trace risk (sum of the individual event risk scores). Figures 4.3 and 4.4 show example trace tables from Figures 2.7 (Trace 8) and 2.9 (Trace 2), respectively.

Event Risks

Event	Likelihood	Impact	Risk Score
unsafe_weather	0.5	5	2.5
weather_unsafe	0.5	5	2.5

Total Trace Risk: 5

Figure 4.3. Risk table accompanying Figure 2.7 of SAR Expansion model in Chapter 2 of this report. Source: [9].



Event Risks

Event	Likelihood	Impact	Risk Score
man_overboard_r	0.7	8	5.6

Total Trace Risk:
5.6

Figure 4.4. Risk table accompanying Figure 2.9 of SAR Expansion model in Chapter 2 of this report. Source: [9].

With each trace having a risk factor calculated from event traces with nonzero risk attributes, a query is used to build a global report on total risk, highest risk, and average risk (Figure 4.5). Directions for sorting by traces with a risk factor greater than 9 are also printed in the bottom compartment of the report.

Risk Report for
Scope 1

Total risk over 8
traces (sum of
trace risk scores):
49.8

Highest Risk: 11.2
(trace 1)

Average Risk:
6.225

Sort by Marked to
view traces with
above average
risk >=9.

Figure 4.5. Global Risk Report for final SAR Expansion model at Scope 1 (accompanying Figures 2.5, 2.7, 2.9, and 2.10 of this report; all traces found in final MP model from SAR Expansion Team). Source: [9].

Risk analysis in MP has been a topic of Masters thesis research by NPS graduates Moebius [13] and Palmieri [14] and is demonstrated in MP-Firebird preloaded models (Import menu, Application_examples folder) called "Aquaticus_Competition_Search_and_Rescue" and "Supply_Chain_with_Two_Cyber_Threats."

CHAPTER 5:
Conclusions

5.1 Findings

This research set out with the following objectives:

1. Refine intern-authored models of the Aquaticus game rules and autonomy algorithms,
2. Advance the description of those algorithms with state diagrams, and
3. Conduct a risk analysis for all generated event traces.

Objectives 1 and 3 were addressed by the following research questions:

1. What are the potential blue team, red team, and environment behavior possibilities for an Aquaticus competition?
2. Which event traces adhere to the Aquaticus rules? Are there any event traces that violate the rules?
3. Which events in the game present a risk to the blue team (with likelihood and impact attributes), and which scenarios carry the largest and smallest risks?

In answer to Question 1, the potential blue team, red team, and environment behavior possibilities for an Aquaticus competition were modeled by a team of interns [7] and described in Chapter 2. A total of 32 traces were generated in a minimally-constrained early draft model, and a total of eight traces were generated in the final, well-constrained model. Each of the eight final model traces represents one potential behavior possibility for the blue team, red team, and environment for the events that were modeled. The final model [9] is available on MP-Firebird in the Import menu Application_examples folder, titled "Aquaticus_Competition_Search_and_Rescue."

In answer to Question 2, all eight event traces that were produced in the final model adhere to the Aquaticus game rules. In the initial minimally-constrained model, two traces were found to contain behaviors that violated the game rules or command intent. One of the two traces showed two different violations in the same trace, making the total count of violations to three. Chapter 2 discusses these traces in detail.

In answer to Question 3, the following events in the game were characterized with risk attributes of likelihood and impact:

1. man_overboard_r
2. man_overboard_b
3. robot_in_danger_r
4. robot_in_danger_b
5. unsafe_weather
6. weather_unsafe
7. continue_playing_r
8. continue_playing_b

As indicated by the "r" and "b" subscripts, the risk analysis accounted for not only blue team events but also for red team events. As shown in Chapter 4, risk factors were computed for each trace to inform overall risk statistics across the entire model, including a total risk (sum of all trace risk factors) of 49.8 and a maximum risk of 11.2 (trace 1). An average risk of 6.225 was also computed across all eight traces. The numerical values chosen for the risk attributes of likelihood and impact were notional for a demonstration of risk analysis in MP.

Objective 2 was addressed with the development of the state machine model of robot behavior algorithms described in 3. This model serves to demonstrate that the state transition modeling paradigm can be implemented in Monterey Phoenix. This work also showed that the logic behind the modeled state diagram is correct (as verified by the state diagram matching the intended specification) and that it is complete up to scope 1 (full coverage of possible traces through the state diagram). The final model [12] is available on MP-Firebird in the Import menu Application_examples folder, titled "Aquaticus_Competition_State_Machine_Diagram."

The methodology tested in this research can be used and repeated on other missions, systems and processes of specific interest to the Deputy Commandant for Information. Ideally, the United States Marine Corps can grow a native MP-enabled emergent behavior analysis capability and translate insights gained from the synthetic scenarios generated by MP into properties of real missions, systems, and processes.

5.2 Recommendations for Future Work

The intent is to have the 2023 MPVIP leverage the findings and products of this research to continue efforts to capture computable models of command intent/human intent for mission-level tasks and lower-level tasks using the MP environment. Specifically, the Aquaticus SAR model should be expanded with more behaviors, the state machine model extended and revised with more and different states and transitions, and the numerical values used for the risk calculations should be fine-tuned and validated. Efforts will continue to improve the MP ability to generate finite state machines to experiment with measuring human-robot team latencies associated with decision loops to react to current events. Efforts will also continue to improve the interface between MP human-intent-discrete-event-logical-behavior-models and simulation environments for physical-constraint-continuous-dynamics-physical-behavior-models, which will make progress in linking acquisition decisions made with these other tools to data and decisions that can be made with MP. One such tool is an autonomy stack known as the Mission Oriented Operating Suite - Interval Programming (MOOS-IvP), which supports optimizes behavior coordination among autonomous marine vehicles. USMA interns demonstrated that MP finite state machine model(s) can drive the programmed behaviors in MOOS-IvP. Future work could extend the interns' approach to controlling human-robot physical dynamics and using MP to generate additional asynchronous and aperiodic finite state machines, including "loop" behaviors capable of executing an arbitrary number of discrete-event cyclic "loops" of discrete event behaviors. These loops are characteristic of synchronous machines and can be made to be synchronous and periodic with a "heartbeat" of the slowest period. This is how computer-controlled machines are constructed and can be experimented with as abstract simulations, and whose finite state machines can be ran on individual robots or integrated into force-on-force physical experiments such as MDO-HuRT-S.

Further research should continue to explore how the Aquaticus SAR model and the state machine model support acquisition decision-making and risk analysis in the context of mission-level events and lower-level tasks. Many factors can influence acquisition decisions and risk analysis, including the complexity and uncertainty of the task, the resources, capabilities available to the organization, and the potential consequences of different courses of action. An improved understanding of the Aquaticus SAR model and the state machine model events and tasks can be used to evaluate and prioritize different options and make informed decisions that minimize risk and optimize outcomes more effectively.

List of References

[1] M. Auguston, “Monterey Phoenix, or how to make software architecture executable,” in *Proceedings of the 24th ACM SIGPLAN conference companion on Object oriented programming systems languages and applications*. Orlando, FL: ACM, 2009, pp. 1031–1038.

[2] Naval Postgraduate School, “Monterey Phoenix Website.” Accessed Dec. 13, 2022 [Online]. Available: https://www.nps.edu/mp/

[3] S. Easterbrook, R. Lutz, and R. Covington, “Experiences using lightweight formal methods for requirements modeling,” vol. 24, no. 1, pp. 4–14, 1998.

[4] J. Woodcock, P. G. Larsen, J. Bicarregui, and J. Fitzgerald, “Formal methods: practice and experience,” *ACM Computer Surveys*, vol. 41, no. 4, pp. 1–40, 2009.

[5] Naval Postgraduate School, “MP-Firebird Tool.” Accessed Dec. 13, 2022 [Online]. Available: https://firebird.nps.edu

[6] Naval Postgraduate School, “MP-Gryphon Tool.” Accessed Dec. 13, 2022 [Online]. Available: https://www.nps.edu/mp/gryphon/

[7] L. Mattson, V. Patel, and M. Sagos, “Human-robot teaming: Sar expansion,” MPVIP Cohort 4 Showcase Presentation, United States Military Academy Robotics Research Center, West Point, NY, USA, Summer 2022.

[8] M. Trice and M. May, “Aspire competency assessment,” MPVIP Cohort 4 Showcase Presentation, Department of Veterans Affairs, National Artificial Intelligence Institute, Washington, DC, USA, Summer 2022.

[9] L. Mattson, V. Patel, and M. Sagos, *Human-Robot Teaming: SAR Expansion*, MPVIP Cohort 4 Monterey Phoenix Model, West Point, NY, USA, Summer 2022 [Online]. Available: https://gitlab.nps.edu/monterey-phoenix/mp-model-collection/preloaded-examples/-/blob/master/models/Application_examples/Aquaticus_Competition_Search_and_Rescue.mp

[10] M. Trice and M. May, *ASPIRE Competency Assessment*, MPVIP Cohort 4 Monterey Phoenix Model, Washington, DC, USA, Summer 2022 [Online]. Available: https://gitlab.nps.edu/monterey-phoenix/mp-model-collection/preloaded-examples/-/blob/master/models/Application_examples/ASPIRE_Competency_Assessment_Context.mp

[11] T. Errico, “Human-robot teaming: State machine,” MPVIP Cohort 4 Showcase Presentation, United States Military Academy Robotics Research Center, West Point, NY, USA, Summer 2022.

[12] T. Errico, *Human-Robot Teaming: State Machine*, MPVIP Cohort 4 Monterey Phoenix Model, West Point, NY, USA, Summer 2022 [Online]. Available: https://gitlab.nps.edu/monterey-phoenix/mp-model-collection/preloaded-examples/-/blob/master/models/Application_examples/Aquaticus_Competition_State_Machine_Diagram.mp

[13] R. C. Moebius, “Methods and tool for risk analysis based on behavior models utilizing Monterey Phoenix,” Masters, Naval Postgraduate School, 2018.

[14] M. Palmieri, “Assessing and visualizing risk in Monterey Phoenix through a supply chain cyber-attack use case,” Masters, Naval Postgraduate School, 2021.

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