# Use of Situation and Risk Modeling in Guidance Solutions

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Abstract—Guidance, Navigation, and Control (GN&C) systems take data from the environment to create a mathematical representation of the system state. The system's guidance solution is then determined from this navigation solution and is typically a minimization of some objective weight function, J. This objective function is a time, cost, weight, or other physically realizable quantity. In this paper we show a method to create a guidance solution based upon system risk for a system's goal. The methodology presented uses a goal to create a situation. The situation assessment creates a situation model whose risk can be determined. The projection of this into the future then creates a trajectory for the system to follow. A simulation of using nautical vessels is shown and compared to traditional optimization methods.

Keywords—collision avoidance, risk analysis, GN&C, guidance, situation assessment, trajectory optimization

### I. INTRODUCTION

The first guidance system, as rudimentary as it was by today's standards, was developed by Goddard for use in his rocket experiments. From that point until the mid 1960's guidance systems were mostly the domain of rocket systems since these were the only vehicles made that were autonomous. However, since the 1970's guidance systems made their way into multiple different applications as smaller, and more powerful computer processing allowed for automation of many different dynamic systems. We are now at a point where nearly all of our everyday objects contain some type of guidance system. Interestingly for purposes of this paper all of these guidance systems have the same general structure and methodologies. In this paper we intend to propose a new paradigm.

We define guidance as the algorithm that takes data from the navigation state and creates a trajectory that moves the system from its current state to some future state, and minimizes some cost function, subject to some physical constraints.

$$\min f\left(\vec{x}, \vec{u}\right)$$
  
s.t.  $\frac{d\vec{x}}{dt} = g\left(\vec{x}, \vec{u}\right), \ \left|\vec{u}\right| \le \vec{c}, \ \vec{x}(\tau) \neq \vec{\Xi}(\tau)$  (1)

In (1)  $\vec{x}$  and  $\vec{u}$  are estimated by the system from the navigation system. The cost function, f, is a function to minimize the energy expense in performing the system's desired goal. This goal is set by the human operator(s). The system constraints are set by the manufacture of the system, and the system's engineers define the state constraints somewhat arbitrarily. These constraints are set such that the entire system does not fail in its overall goal.

In order for a guidance system to work one must have a navigation state. This navigation state is determined by a navigation system, and the goal is to provide the most accurate assessment of the world around the dynamic system. Modern navigation methods began with the work of Draper [1], and continued through the work of Kalman [2] and many others [3],[4],[5],[6]. The navigation subsystem ultimately is attempting to determine what is the situation that the guidance subsystem needs to create a trajectory through. Questions like where am "I", where are "my" targets, what areas are constraints, etc. are determined by the navigation subsystem. This process is shown in Figure 1, below.



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## Fig. 1. Standard guidance, navigation, and control system

It is important to note that the system's state that is determined by the navigation subsystem is a subset of the actual situation that the system is involved in. Both in that the physical states estimated will have an error, and that not all components of the situation will be able to be sensed or analyzed for use in the guidance subsystem. Engineers, as is well known, spend many hours determining which pieces of data are important to the system's goals, and which can be ignored [7].

Effectively guidance and navigation engineers are acting as a-priori situation analysts. However, what happens when the situation does not match the a-priori assumptions of the engineers and system developers? To begin this we start with the seminal work done by Dr. Endsley on Situation Awareness [8]. Dr. Endsley hypothesized that a situation analysis is developed in three levels. The first is determining the entities and states in the environment, the second is understanding the relationship between those entities, and the third is the ability to project the situation into the future.

Further work in this area showed that there was an ontology that defined how one would be aware of a situation [9]. Through this process it was determined that a method to achieve a goal creates a situation. A plan to accomplish a goal will inherently involve many entities, relationships, and dynamics that will create the real world situation. This situation will be analyzed by the entity that created the plan for the goal to determine the best estimate of what the situation actually is. It is important to note that in this framework a plan to accomplish a goal itself creates a situation. This is what system architects and engineers are doing as they develop their guidance and navigation subsystems, and system dynamics.

With this background it is now possible to ask the question what is the probability that a goal will not succeed? The answer to this is the situation risk. With this goal, and this method, what is the probability of failure given the current time situation. It should be noted that a single goal and the plan for that goal creates a situation, and by extension one entity can have n-goals, with m-plans, and each goal-plan combination creates a situation that carries some risk given the current state.

Traditional system engineering methods have the goal of minimization of the cost function through a system's dynamics with the constraints to avoid unwanted state-overlap (collisions). These constraints are based upon some dynamics and analysis of how a specific class of dynamic objects behave [10], [11], [12], [13], [14], [15]. The results of this are seen in COLREGS, TDAS, speed limits on highways, and other system regulations. However, with all of this good work done, multiple collisions occur daily for all manner of dynamic objects.

It is proposed here that a new paradigm be explored; one that uses the goal-plan combination's risk as the objective function to be minimized. The implications of this at first appear subtle, but as it is explored it will be obvious that the traditional method of guidance and navigation are a subset of the situation-risk assessment (SRA) presented.

#### II. PROPOSAL

The process begins with Endsley's situation assessment method. In this method the entity creates a model through the use of the situation assessment. This model is based upon the data and knowledge gathered by the entity about the reality of the situation. Like all models, the situation assessment will not fully match reality. An omniscient 3<sup>rd</sup> party observer, unlike this entity, would know the actual percent difference between the entity's model and reality at any given time. However, the real entity itself will have some confidence on the validity of the model.

In traditional navigation methods, the confidence interval for the situation assessment is the covariance matrix. The covariance matrix is based upon the known uncertainty of the measurements. The difference between these two methods is that the SRA not only attempts to determine the uncertainty about the current system's dynamic states, but also determines the uncertainty that all factors that are actually present in the situation are accounted for. It attempts to provide knowledge on the assessment's unknown-unknowns and the impact to the overall goal that they might have. Between these two uncertainties and the current situation assessment a chance for failure of a goal from a plan is the risk. This new system is shown in Figure 2, below.



Fig. 2. New paradigm for risk based guidance, navigation, and control

Figure 3, below, shows how the SRA paradigm compares to a traditional GN&C system. Notice that there is overlap between these two methods; this overlap is not happenstance, it is part of the conjecture of the authors that this method is a superset of a traditional GN&C system.



Fig. 3. New paradigm GN&C system with old GN&C architecture

One of the main benefits of the RSA methodology is that multiple objectives can be processed at the same time. The agent making the decision what action(s) to perform ultimately has the ability to prioritize those objectives (and by extension the risks) in a somewhat arbitrary fashion. However, the process lends itself to multiple objectives with no change to the system process. This is shown graphically in Figure 4, below.



Fig. 4. Multiple objectives for the SRA methodology

Returning to Endsley's situation awareness model, it is only at level 3 of SA that one can be truly said to be aware of a situation. Level 3, as a reminder, is the ability of the entity to project the current state to a future state. Using the SRA we have implicitly stated that we have achieved some awareness of the situation and thus have some ability to project the current situation state into the future.

In addition to that we have an assessment of risk for those future states. Since our plan is for a goal, that carries with it some risk of non-achievement, it would be best to follow the trajectory that minimizes that risk (and thus maximizes the likelihood of success). If you have a goal of non-collision, and your plan is to sail a vessel through the ocean, each possible trajectory will carry with it some risk of collision. If we were an omniscient 3<sup>rd</sup> person then we would be able to select those trajectories that would precisely avoid a collision. However, since we are limited by our knowledge and awareness each trajectory does carry some risk of goal-non-achievement (or risk). Traditionally the goal of non-collision is handled by exclusions for trajectories. In the RSA method, this goal is automatically handled.

Up until now the discussion has involved the philosophical direction taken. But for this to be anything other than an intellectual exercise, one must show how this can be used in practice. Let us start with a goal of collision avoidance. Risk quantification has been developed extensively in the literature [16], [17], [18], [19], [20], [21], [22], [23], [24]. The COWI group identified a method of assessing collision risk through the parameters of the theater, temporal-geometric orientation, human factors, and machinery that is best suited to a real-time dynamic system [25]. Each of these percentages are conditional probabilities, where the essential question asked, is what is the chance that a collision will occur due to "human factors" given the current state (2).

$$P_C = P_T P_G P_H P_M \tag{2}$$

Since human factors in our system would be another set of risks we are currently ignoring those methods in the current system.

The probability that a collision will occur based upon an object being the same theater means that the objects are in the same vicinity, and that they can see each other. In general this is 1 or 0, but to more accurately give a range of values an inverse tangent function acts to give a continuous range. The probability that two objects are geometrically and temporally linked is an exclusive or Poisson based ratio between their distance and the current trajectories not overlapping.

It should be noted that these conditional probabilities are themselves outcomes of other entity's situations. In (3), we show the probability of collision given an entity's current state.

$$P_{c} = \left(1 - \frac{2}{\pi} \tan^{-1}\left(\frac{d_{ist}}{V_{\max}\tau}\right)\right) \left(e^{\frac{d_{clast}}{d_{cr}}} + \left(1 - e^{\frac{-d_{clast}}{d_{cr}}}\right) \left(1 - \frac{2}{\pi} \tan^{-1}\left(\frac{d_{ist}}{V_{\max}\tau}\right)\right)\right)$$
(3)

For multiple objects the probability is calculated in (4).

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$$P_{Col} = 1 - \prod_{i=1}^{\text{rang}} \left( 1 - P_{C_{O->i}} \right)$$
(4)

If we look at the goal of actually arriving at a given destination we note that the idealized, least distance travel path may not be what is actually undertaken. The other factors considered may cause the proposed trajectory to differ from this ideal. In that case any path that deviates from this course is a non-zero risk of not actually arriving at a destination. In addition, the further away from the target the higher the risk of not arriving will become; essentially the further away one is the more likely something can go wrong.

For this, the theater risk goes from 0 when the distance to target is 0, and 1 when one is "far" away. This gives the risk of not getting to the destination to be (5).

$$P_{W} = \frac{\vec{V} \cdot \vec{d}_{way}}{\left|\vec{V}\right| \left|\vec{d}_{way}\right|} + 1 - e^{-\frac{\left|\vec{d}_{way}\right|}{S_{f}}} - \frac{\vec{V} \cdot \vec{d}_{way}}{\left|\vec{V}\right| \left|\vec{d}_{way}\right|} \left(1 - e^{-\frac{\left|\vec{d}_{way}\right|}{S_{f}}}\right)$$
(5)

This process could be continued for other goals. Examples include following international law, minimization of fuel, etc. For purposes of this paper we will look at these two objectives. It is interesting to note that one does need both objectives to explain the utility of the methodology. Initial testing with a non-collision goal would have all entities do nothing to minimize the risk of collision.

So how do we combine these two risks? The initial thought was to combine the two in a weighted sum (6).

$$Risk = aP_{col} + bP_{W} \tag{6}$$

Where the weights of each equal 1 as defined in (7).

$$a+b=1\tag{7}$$

The other idea is to attempt to clear all risk through a union of the two risks (8).

$$Risk = 1 - \left(1 - P_{col}\right) \left(1 - P_{W}\right) \tag{8}$$

Finally, and not yet attempted, the authors discussed having a dynamic weighting of the risk (9). This would require an overall analysis of the situation that would supersede the decisions of the object.

$$Risk = a(t)P_{col} + b(t)P_{W}$$
(9)

For purposes of this paper the weighted risk addition is used. After some testing we elected to weight the waypoint 65% and the collision 35%. Most sets of weights achieve success, but combinations near 50% or 100% cause the decisions to be inconsistent.

#### **III. SIMULATION RESULTS**

We begin a simulation with 10 TargetShips and one OwnShip. These vessels are simulated to be 5 nautical miles from each other randomly placed (with an initial constant seed) around the origin. OwnShip starts at the origin. OwnShip's goal is 5 nautical miles away in the opposite direction from travel. This is shown in Figure 5, below (distances are in meters). In the plot the final locations are denoted by the number (or 'x'), and OwnShip's waypoint is noted by the 'x' value.



Fig. 5. Ship positions for a 20 min simulation.

We now use a traditional spectral method trajectory optimization on OwnShip (marked by 'x'), to go to its waypoint. This process is shown in Figure 6, below. Notice that it turns and heads towards the waypoint directly as is normally anticipated. However, the method to employ this result requires a lot of assumptions and problem set-up. The development of this method is beyond the scope of this paper, but can be found in the references listed below.



Fig. 6. Traditional path optimization results

We can now compare these traditional results to a greedy algorithm that only chooses the least risky control input. The decision algorithm implemented is very simple, no arbitrary constraints were needed to ensure that the vehicle kept a safe distance from any TargetShip, and no computationally intensive derivatives were needed. In fact the simulation for OwnShip using RSA ran approximately 25% faster on the same hardware and same simulation framework. The results of the RSA model on OwnShip is shown in Figure 7, below.



Fig. 7. Risk-based trajectory decision

Note that we achieve a similar trajectory with fewer assumptions and less engineering time setting up the problem using this method. However, we can also look at the real-time risk of the system. While the decisions were not based upon the risk non-feedback, or traditional methods, risk is intrinsic to how the simulation runs, so we were able to get system-wide risk assessments. Figure 8, below shows the average system risk using no feedback, traditional optimization and the RSA system. Not surprisingly overall system risk was decreased, but it is interesting to note that even though the vessel goes towards the target in the traditional method, the system risk was actually significantly increased.



Fig. 8. Total simulation risk results

Figures 9-a, 9-b, and 9-c show the OwnShip risk change given no feedback, traditional optimization, and risk based decision making.



Fig. 9-a. OwnShip Risk with no feedback



Fig. 9-b. OwnShip risk with traditional guidance



Fig. 9-c. OwnShip risk with risk based decision making

# IV. CONCLUSIONS

In this paper we started by stating that by setting a goal you create a situation to achieve that goal. The chance that the goal will not succeed is the risk associated with the situation. We noted that this viewpoint is a superset of the traditional guidance, navigation, and control problem that has been studied since the 1950's. By using this observation we were able to create a simple simulation that was able to achieve better results than the traditional trajectory optimization based guidance systems.

More importantly the background to get to that point showed that the traditional GN&C problem is a subset of the greater situational awareness problem. By using this superset problem we have more flexibility in the types of goals that can be automated.

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