

Testing a Nonveridical Aircraft Collision Avoidance System

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ABSTRACT

Map displays are veridical representations of realistic information. State spaces are *nonveridical* representations of arbitrary n -dimensional information. In this experiment, flight performance using a map-based cockpit display of traffic information (CDTI) was compared to performance augmented by a state space-based 4D collision avoidance system (CDTI+4CAS). 4CAS displayed state information about the safety of ownship maneuvers and their available maneuver time. Twelve general aviation pilots each flew eight scenarios, trying to deviate as little as possible from course while still maintaining standard enroute separation from traffic. The CDTI+4CAS condition showed performance superiority over the CDTI-only condition for five of five dependent measures of maneuver efficiency, four of four measures of maneuver safety, and six of nine measures of workload. Human factors issues are discussed.

INTRODUCTION

STATE SPACES — The term *veridical* means “coinciding with, or representing, physical reality.” A typical map is a top-down veridical view of part of the physical world.

In contrast, state spaces are *nonveridical* information representations commonly used in fields such as chemistry and physics. A state space can be constructed from any arbitrary features that can be classified or quantified. Figure 1 shows a hypothetical 4D state space representing chemical reaction speed at various combinations of temperature, pressure, and enzyme concentration.

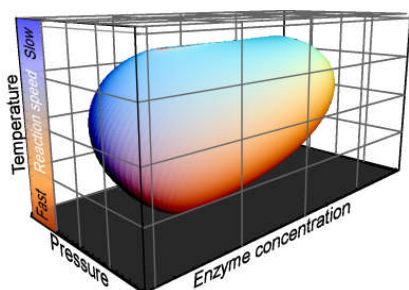


Figure 1. A 4D state space based on temperature, pressure, and enzyme concentration. Color would depict reaction speed.

State spaces are useful for the display of abstract, multi-dimensional data, particularly where interactions occur between certain combinations of axis values. Such complex interactions can be difficult to describe mathematically, yet easy to visualize within a state space. Such ease of visualization can allow control displays with sophisticated authority over complex systems, even by relatively untrained users.

The present research examines a nonveridical, multidimensional state space control display—specifically, one intended to help keep aircraft safely separated.

VERIDICAL TRAFFIC DISPLAYS — Veridical displays of traffic information (DTI) have been developed in numerous forms, ranging from familiar map-view ATC displays and cockpit displays of traffic information (CDTI), all the way to sophisticated 2D veridical conflict resolution displays (1), coplanar displays (2, 3), and even 3D veridical displays (4, 5, 6). Many systems make use of advanced separation-maintenance technology to predict and resolve conflicts between aircraft. Cockpit variants of veridical *collision avoidance systems* (CAS) have also been developed (1, 7). The most widely known system is TCAS ([Traffic Alert and Collision Avoidance System], 8). However, TCAS has a short lookahead time, insufficient for strategic traffic planning. Therefore, a number of developers have focused on systems with lookaheads sufficiently long to allow gentle aircraft maneuvers.

One of the usability issues common to all these efforts involves the difficulty of veridically displaying certain critical types of aircraft maneuver information. Specifically, veridical displays have trouble representing maneuver *combinations*—simultaneous changes in aircraft speed, heading, and/or altitude. Moreover, the informational complexity of veridical displays rises exponentially with the number of aircraft displayed since the number of pairwise interactions between n aircraft is $n(n-1)/2$.

In response, some developers have begun using elements of nonveridical display. For instance, Van Dam, Appleton, Mulder, and van Paassen (9) developed a CDTI that nonveridically represents aircraft speed, allowing speed+heading combination maneuvers. This device has demonstrated its effectiveness on difficult air traffic scenarios.

MANEUVER SPACE — To fully address the underlying data visualization problems inherent to crowded airspaces, Knecht and Smith (10) conceptualized a representational “space constructed of maneuvers”—a *maneuver space* (MS). Figure 2 illustrates how an aircraft autopilot serves as a basis for such a space.



Figure 2. An aircraft autopilot, showing its three “dimensions” of heading, airspeed, and altitude. These dimensions form the three coordinate axes of maneuver space (MS).

Maneuver space is essentially just a 3D picture of “safe-vs.-unsafe” autopilot settings. Color is used to represent predicted time-until-loss-of-separation for each possible maneuver. Thus, the overall space is 4-dimensional.

Technical definition — The technical definition of maneuver space is a 4D state space unique to each aircraft, dimensionalized by that aircraft’s a) heading, b) speed, c) altitude, and d) available maneuver time. MS represents all conflictual and non-conflictual maneuvers achievable by one aircraft within a fixed time lookahead, given the obstacles predicted along each potential maneuver’s hypothesized path.

MS properties — Maneuver space has eight primary properties. Below, the symbol “≡” will mean “is equivalent to.” Figure 4 provides a reference.

- 1) Each cube within MS ≡ **one maneuver** ≡ one discrete setting of the autopilot.
- 2) Moving inside MS
 - a) **left or right** ≡ **heading change**
 - b) **in or out** ≡ **speed change**
 - c) **up or down** ≡ **altitude change**
- 3) **Colored MS** ≡ “unsafe” (→ separation failure).
- 4) **Color** ≡ **available maneuver time** (minutes remaining until a given maneuver → separation failure).
 - a) **black** ≡ **no immediate conflict**
 - b) **dark green** ≡ **6 minutes** to separation failure
 - c) **yellow** ≡ **3** “ “ “ “
 - d) **magenta** ≡ **0** “ “ “ “
- 5) The **3D center of MS** ≡ **current autopilot setting**.
- 6) Therefore, **no avoidance is needed unless MS-center is colored**.
- 7) Maneuvers in conflict with > 1 obstacle are colored for the conflict *closest in time*.
- 8) Cubes are translucent, letting us see through the entire MS.

The color black is merely the “color of empty space.” Therefore, a “black” cube is technically just a colorless translucent cube denoting a safe maneuver.

These definitions may seem complicated. In practice, they become quite simple after a few minutes flying the actual device. To illustrate, Figure 3 shows a map view

of a hypothetical situation where the pilot’s own ship (ownship) must maneuver to avoid two intruders.

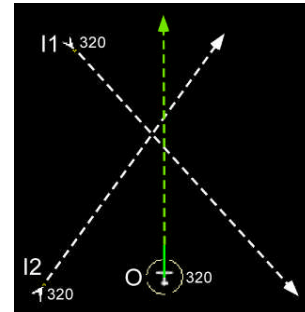


Figure 3. Hypothetical example of three aircraft, all at 290 kt indicated airspeed (.78 mach) and flight level 32,000 (FL 320). The ownship (O) must maneuver to avoid two intruders (I1, I2)

Figure 4 shows Figure 3 translated into the domain of MS. Notice the translucent, glasslike structure of cubes within an otherwise-black MS. This structure is a *conflict region* (CR). A CR is a set of numerically contiguous maneuvers predicted to be unsafe by a hardware/software *conflict probe* (8, 11), given the system lookahead time of 6 minutes. Quite literally, CRs represent “bad maneuvers.” Note how they “pop out,” visually.

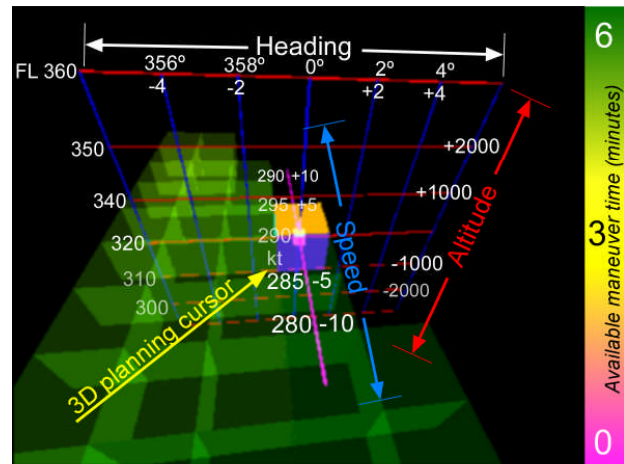


Figure 4. A slightly downward-looking view of how the veridical situation of Figure 3 transforms into 4D nonveridical maneuver space. Color would depict available maneuver time for each problematic maneuver.

If (and only if) a CR overlaps the center of the display must we maneuver (because Property 5 defines display center as being our current course).

In practice, we graphically rotate the MS briefly to inspect CRs from different angles. If necessary, we move a 3D planning cursor to select an efficient avoidance maneuver. By definition, this will be one that deviates minimally from 3D display center (Cartesian 0,0,0).

Now, consider the following: Figure 3 shows a situation easily solved by an altitude change. But, suppose there

were a more efficient heading or speed solution, or a combination solution. Suppose the intruders were climbing, descending, or turning. Suppose there was additional traffic at additional altitudes. In that case, the trivial altitude solution evaporates. And, even if a CDTI were also 3D, rotatable, equipped with a conflict probe, and with some way to visualize potential maneuver solutions—how could the 4D multiplicity of solution choices and available maneuver times be displayed in a simple, unambiguous way? To date, such veridical technology is non-existent.

In contrast, a MS-based display makes all individual and combination maneuver solutions plain. Safe and unsafe maneuvers stand in stark contrast to one another. To avoid all known threats, no matter how many and regardless of how complex the traffic geometry, we simply move the 3D planning cursor to a black “safe” zone and then hit an EXECUTE button to reset the aircraft autopilot. With practice, this process can be done in seconds.

PROOF OF CONCEPT — It is clear that MS displays are not intended to replace veridical displays of traffic information—merely to augment them. Therefore, the best way to test an MS-based system is to see if it adds value to a DTI in terms of operator performance.

Experiment 1 — A prototype 4-dimensional collision avoidance system called 4CAS was first built and tested (12). Briefly, eight male general aviation (GA) pilots flew nominal straight-line courses threatened by traffic. CDTI-only trials (with no conflict alert or resolution capability) were compared to 4CAS+CDTI trials. With 4CAS present, average path length, maneuver onset time, and

duration of pilot deviations were significantly shorter, and enjoyability-of-use was reported as significantly greater.

Experiment 1 led to system revisions, after which the system was retested. Experiment 2 follows below.

METHOD

PARTICIPANTS — Twelve GA pilots volunteered with informed consent, 11 male, one female. Median pilot age was 23.5 (range 19-63, mean 27.8, SD 12.1). Median flight hours was 701 (range 70-8000, mean 1271, SD 2185). All pilots held a private license, 10 held instrument ratings, six were certified as both Certified Flight Instructor (CFI) and Certified Flight Instructor-Instrument (CFII), seven held Commercial ratings. One held the Air Transport Pilot (ATP) rating.

APPARATUS — The part-task flight simulator is described in (12). The Microsoft Flight Simulator 2004 Boeing 737-400 model was used in conjunction with FS2004 Artificial Intelligence (AI) Traffic to create simulated en-route air traffic and generate recordable latitudes, longitudes, headings, ground speeds, and vertical speeds for ownship and traffic. Both the 4CAS display and a CDTI were provided to pilots.

The CDTI — Figure 5 (right) shows a veridical, top-down, moving map of a typical traffic situation, with the ownship icon occupying display-center. Traffic was depicted as chevrons aimed in the direction of travel. In these initial tests, the CDTI had no conflict alert or resolution capability.

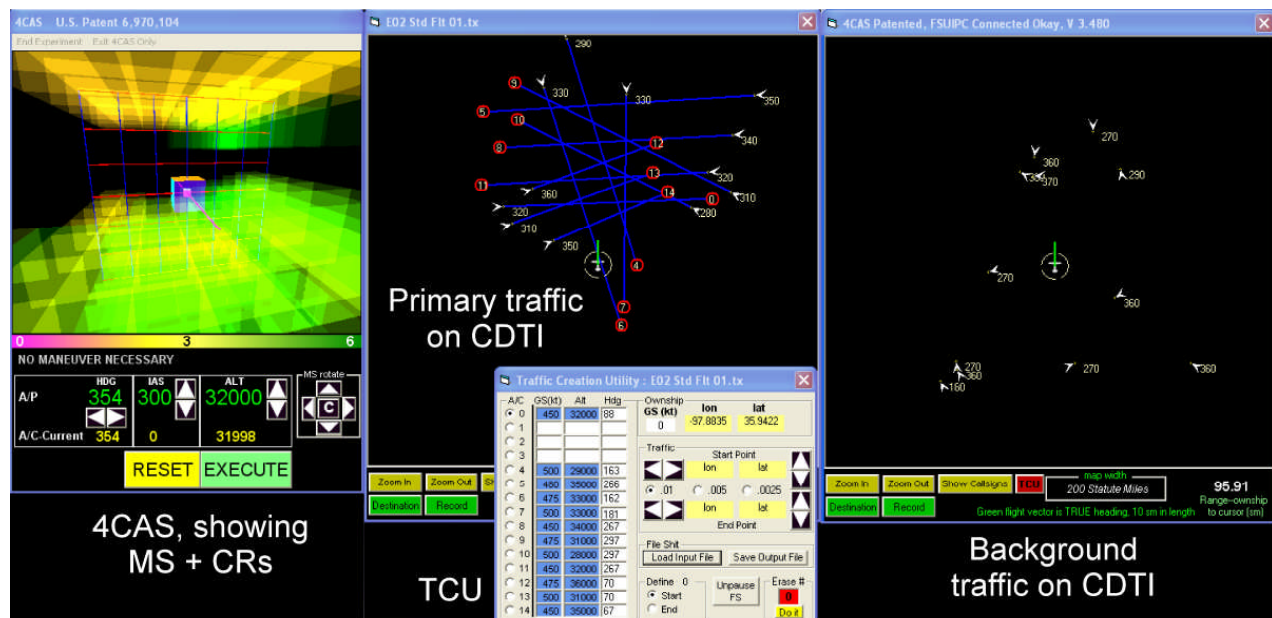


Figure 5. (Left) 4CAS display. Grid and color scales were similar to Figure 4. (Middle) Primary traffic used to create scenario 1, plus the Traffic Creation Utility panel. Blue traffic paths were visible only during scenario creation, not at runtime. (Right) Background traffic used in all scenarios. Each scenario's total traffic was created by convolving primary and background traffic onto a single CDTI.