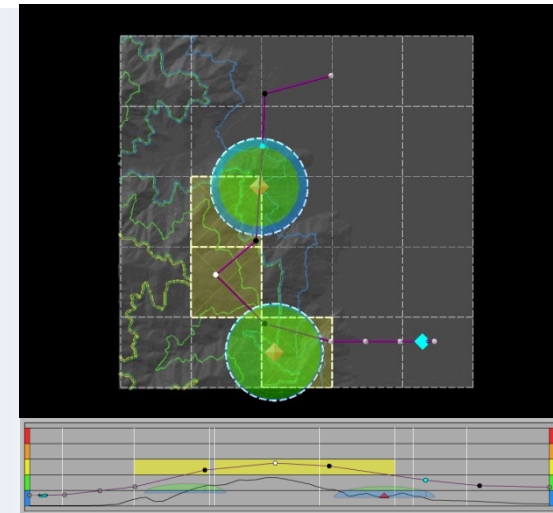




Pacific Science
& Engineering



When Plans Change: Task Analysis and Taxonomy of 3D Situation Awareness Challenges of UAV Replanning



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Pacific Science & Engineering Group
San Diego, CA

15th ICCRTS, 22-24 June, 2010, Santa Monica, CA
Track 8: C2 Assessment Tools and Metrics

UAV operator human factors challenges

- Complex tasks
- High workload
- Multiple competing constraints
- Dynamic environments
- Display-mediated interactions



From U.S Customs and Border Protection

Project overview

- Problem: UAV operator challenge of rerouting UAVs on-the-fly
 - Complex 3D environment
 - Conflicting dynamic constraints
- Approach and solutions

“Should I go left, right, up, down?”
 “How will I get imagery?”
 “If I go right, will I stay under closed airspace?”

1 Analyze replanning problem

Cognitive Task Analysis
3D challenges of UAV replanning

2 Improve display visualizations

3 Introduce path planning automation (PPA)

- Benefits
 - Improved operator situation awareness
 - Faster, less error-prone rerouting



Current work in wider context

- Complex multi-faceted UAV research space
- How is current work *unique*?
 - 3D spatial awareness replanning challenges
- Why is current work *necessary*?
 - Problem analysis is necessary precursor
 - Guides assessment and metrics
 - Guides design of display and automation solutions

supervisory control
adaptive automation

automation
planning & replanning
path finding

aviation & ATC
airspace management

UAV research space

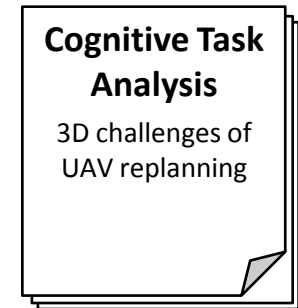
operator displays
synthetic vision
spatial awareness
ground control stations
single & multiple vehicle control

communication
team consensus & collaboration
crew management & selection

McCarley & Wickens, 2005, for review

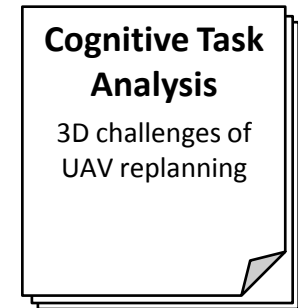
Cognitive task analysis (CTA)

- Purpose
 - Enumerate specific 3D cognitive/perceptual challenges of replanning
- Method
 - Structured interviews w/4 Navy VC-6 Shadow UAV operators
 - Topic areas
 - » Background and context
 - » Replanning event triggers
 - » Replanning goals and strategies
 - » Current display features



Cognitive task analysis (CTA)

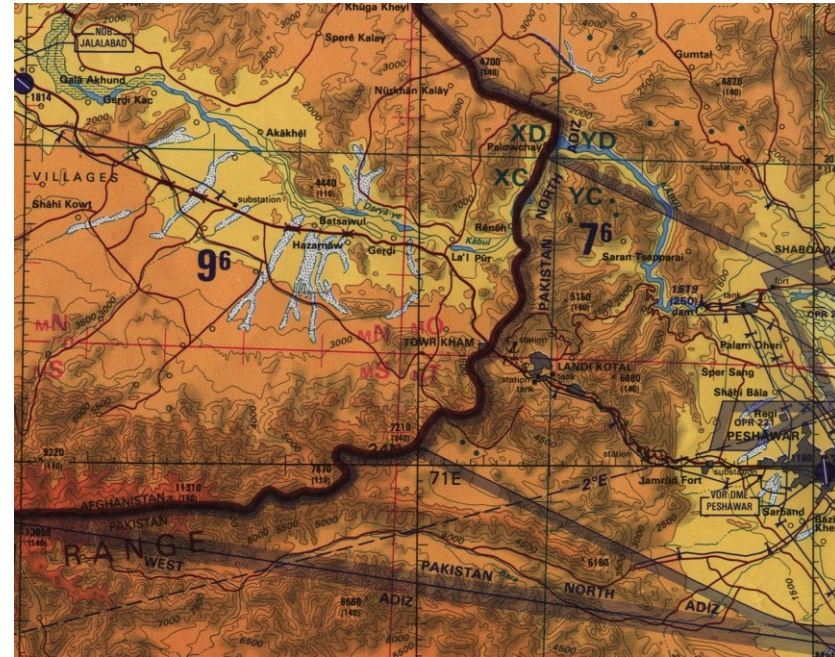
- General findings
 - Frequent need to replan
 - » Dynamic targets
 - » Congested airspace
 - Multiple event triggers, different shapes
 - Replanning entails understanding & resolving competing 3D constraints
 - Time-constrained replanning → satisficing strategy
 - Poorly supported by current displays



Current operator map displays

- 2D topo maps (TPC format)
- Terrain altitude
- Occasional profile view

- Display challenges
 - Cluttered
 - Limited in conveying shape & 3D scene layout (St. John et al., 2001)
 - Difficult to integrate top-down and profile views (Haskell & Wickens, 1993)



From *Tactical Pilotage Chart TPC G-6C*, U.S. Defense Mapping Agency

CTA specific results

- Enumerated rerouting event triggers
 - Target tracking changes
 - Airspace availability
 - Aircraft avoidance
 - Counter-detection requirements
 - Weather avoidance
 - Terrain considerations
- Identified key attributes related to each event
 - Spatial requirements, and action (approach, avoid)
 - Relative frequency
 - Time pressure
 - HF display intervention

CTA results codified in taxonomy

- Organized results into taxonomy
- Events ordered by spatial aspects and relative frequency
- Display requirements applied to task-display dichotomy (St. John, Cowen, Smallman & Oonk, 2001)
 - 2D for relative position
 - 3D for shape understanding and layout

| Rerouting event trigger | Spatial aspects of rerouting goal | Other rerouting requirements | Relative frequency | Time pressure | Event shape understanding requirements | Event relative position requirements | Potential HF leverage points |
|-------------------------|-----------------------------------|------------------------------|--------------------|---------------|--|--------------------------------------|------------------------------|
|-------------------------|-----------------------------------|------------------------------|--------------------|---------------|--|--------------------------------------|------------------------------|

| Rerouting event trigger | Spatial aspects of rerouting goal | Other rerouting requirements | Relative frequency | Time pressure | Event shape understanding requirements | Event relative position requirements | Potential HF leverage points |
|--|---|---|--------------------|---------------|--|---|---|
| New/change to target tracking requirement | Stay within LoS region for target ISR. | <ul style="list-style-type: none"> Remain within cleared airspace Avoid terrain Avoid other aircraft | High | High | Target visibility profile shape | Distance and angles of target | Specify optimal coverage of target in 3 dimensions. |
| Change in airspace availability | Avoid restricted airspace. Stay within available airspace. | <ul style="list-style-type: none"> Satisfy target tracking requirements Avoid terrain Avoid other aircraft | High | Medium | Configuration of available airspace | Distance and angles of available airspace | Make airspace boundaries explicit. Show available and closed airspace. |
| Aircraft avoidance | Avoid airspace region occupied by other aircraft. | <ul style="list-style-type: none"> Satisfy target tracking requirements Remain within cleared airspace Avoid terrain | High | High | Aircraft avoidance region shape | Distance and angles of aircraft | Make location of other aircraft explicit. Provide airspace transit times, distances, and relative position. |
| Counter-detection | Avoid detection region. | <ul style="list-style-type: none"> Satisfy target tracking requirements Remain within cleared airspace Avoid terrain Avoid other aircraft | Low | Medium | Counter-detection region shape | Distance and angles of counter-detection region | Convey shape understanding of counter-detection regions and their relation to terrain. |
| Weather avoidance | Avoid weather region. | <ul style="list-style-type: none"> Satisfy target tracking requirements Remain within cleared airspace Avoid terrain Avoid other aircraft | Low | Medium | Weather avoidance region | Distance from weather region | Convey location and shape understanding information of hazardous weather. |
| Terrain | Avoid collision with terrain. Avoid LoS occlusion from terrain. Land safely on terrain. | <ul style="list-style-type: none"> Satisfy target tracking requirements Remain within cleared airspace Avoid other aircraft | Constant | Medium | Gross terrain shape | Distance and angles of terrain | Convey both shape understanding about terrain and precise relative position information about distances. |

CTA results codified in taxonomy

| Rerouting event trigger | Spatial aspects of rerouting goal | Other rerouting requirements | Relative frequency | Time pressure | Event shape understanding requirements | Event relative position requirements | Potential HF leverage points |
|--|--|---|--------------------|---------------|--|---|--|
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CTA results inform synthetic replanning task

Conducted CTA of 3D spatial awareness challenges of UAV replanning



Cognitive Task Analysis
3D challenges of UAV replanning

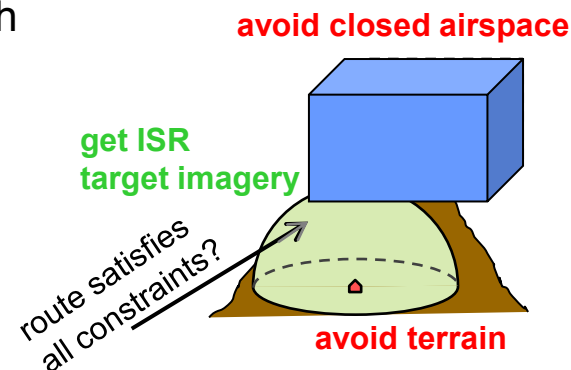
Replanning event taxonomy

| Replanning event (type) | Spatial aspects of replanning goal | Observing requirements | Addressed | Time pressure | Event shape/visibility | Event volume/altitude | Distance of observer | Distance of target |
|--|--|--|-----------|---------------|------------------------------------|--|--|---|
| Target tracking | Identify, locate, and track target | • Identify location of target • Identify altitude of target | High | High | Target visibility profile/shape | Distance and angle of target | Distance and angle of target | Specific vertical location of target in 3 dimensions |
| Change in obstacle availability | Identify obstacle presence Determine obstacle location | • Identify target tracking requirements • Avoid terrain • Avoid other aircraft | High | Medium | Configuration of obstacle presence | Distance and angle of obstacle presence | Distance and angle of obstacle presence | Make airspace reservations Determine altitude and avoid altitude |
| Aircraft avoidance | Identify aircraft presence Identify aircraft location | • Identify target tracking requirements • Avoid terrain • Avoid other aircraft | High | High | Aircraft presence profile/shape | Distance and angle of aircraft | Distance and angle of aircraft | Make location of other aircraft available • Provide as much threat information as possible |
| Counter-avoidance | Identify avoidance region | • Identify target tracking requirements • Avoid terrain • Avoid other aircraft | Low | Medium | Counter-avoidance region shape | Distance and angle of counter-avoidance region | Distance and angle of counter-avoidance region | Counter-avoidance region of other aircraft |
| Weather avoidance | Identify weather region | • Identify target tracking requirements • Avoid terrain • Avoid other aircraft | Low | Medium | Weather avoidance region | Distance from weather region | Distance from weather region | Consider location and shape understanding of weather |
| Terrain | Identify terrain location Identify terrain height Identify terrain slope | • Identify target tracking requirements • Avoid terrain • Avoid other aircraft | Constant | Medium | Terrain profile/shape | Distance and angle of terrain | Distance and angle of terrain | Consider both shape and location of terrain • Provide as much threat information as possible |



Designed synthetic replanning task with abstracted 3D constraints

- Actions: avoid, approach, avoid + approach
- 3D constraints: airspace, targets, terrain
- Kinematic constraints
- Time pressure



Testbed for studying UAV replanning

UAV Testbed: Experiment 1

PACIFIC SCIENCE & ENGINEERING GROUP
 9180 Brown Deer Road | San Diego CA 92121 | (658) 535-1661
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| P | B0 | B1 | B2 | B3 | B4 | B5 | B6 |
|----|------|------|------|------|------|------|------|
| 32 | Scn6 | Scn1 | Scn3 | Scn4 | Scn6 | Scn7 | |
| 33 | Scn6 | Scn4 | Scn4 | Scn1 | Scn7 | Scn0 | Scn8 |
| 34 | Scn6 | Scn4 | Scn7 | Scn3 | Scn8 | Scn1 | Scn8 |
| 35 | Scn6 | Scn7 | Scn6 | Scn4 | Scn1 | Scn3 | Scn1 |
| 36 | Scn6 | Scn8 | Scn0 | Scn7 | Scn1 | Scn4 | Scn3 |
| 37 | Scn6 | Scn0 | Scn1 | Scn8 | Scn3 | Scn7 | Scn4 |
| 38 | Scn6 | Scn1 | Scn3 | Scn0 | Scn4 | Scn8 | Scn7 |
| 39 | Scn6 | Scn3 | Scn4 | Scn1 | Scn7 | Scn0 | Scn8 |
| 40 | Scn6 | Scn4 | Scn7 | Scn3 | Scn8 | Scn1 | Scn0 |
| 41 | Scn6 | Scn7 | Scn8 | Scn0 | Scn3 | Scn1 | Scn0 |
| 42 | Scn6 | Scn8 | Scn0 | Scn7 | Scn1 | Scn4 | Scn3 |
| 43 | Scn6 | Scn0 | Scn1 | Scn8 | Scn3 | Scn7 | Scn4 |

Scenario Editor Demo
 Scenario Player Data Collection

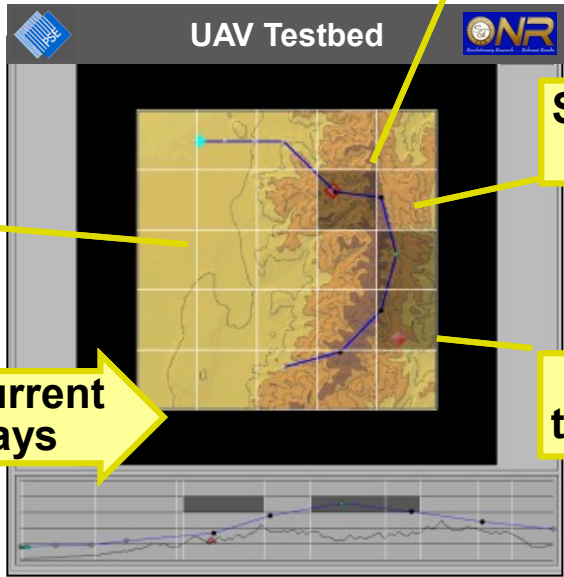
Operationally valid measures of performance

Alternate modes

Specific configurations of 3D replanning constraints

Customizable display formats, interface settings

UAV Testbed



Synthetic task

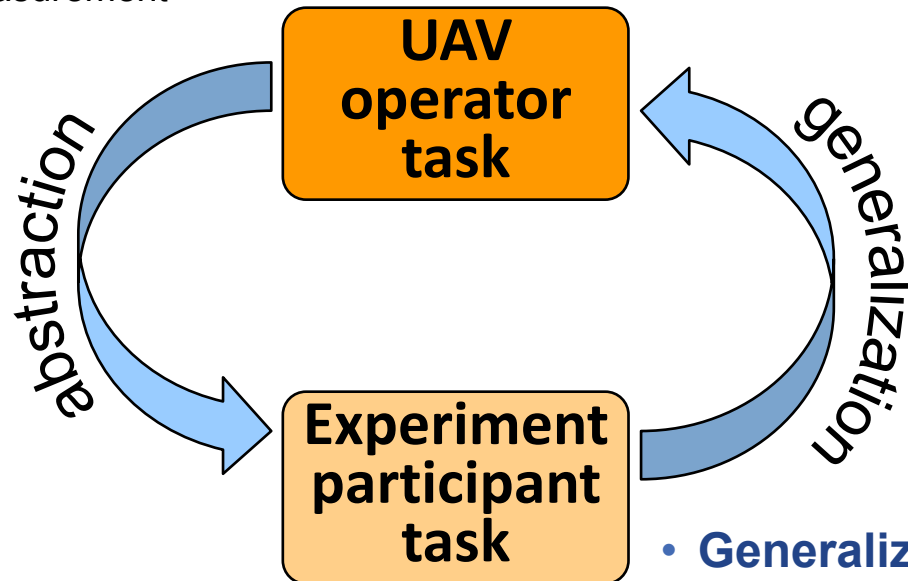
Real terrain



Key features of current GCS map displays

Synthetic task abstraction

- **Abstract** essential elements of real UAV replanning into synthetic task
 - Greater experimental control
 - Reduced time needed for simplified task
 - Consistency across participants
 - Allows sensitive measurement

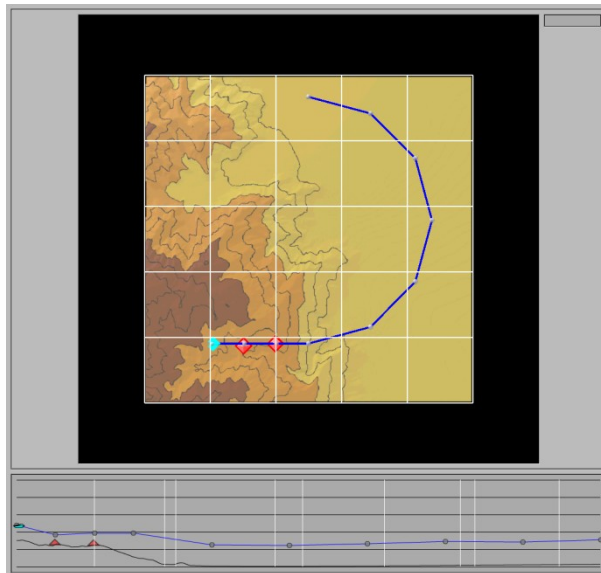


- **Generalize** results back to real-world UAV replanning
 - Similar 3D replanning challenges
 - Similar display features
 - Similar time constraints

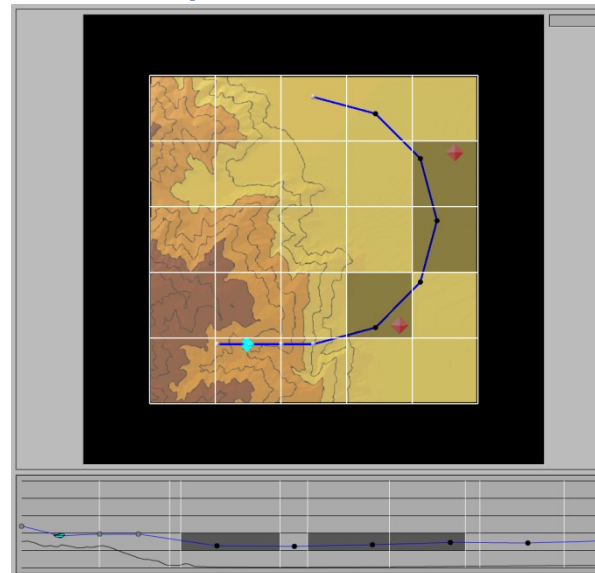
Exp 1: Validate CTA

- Purpose
 - Experimentally validate CTA, measure replanning
 - Baseline for replanning interventions
- Task: Replan UAV routes to satisfy emerging requirements (airspace, targets)

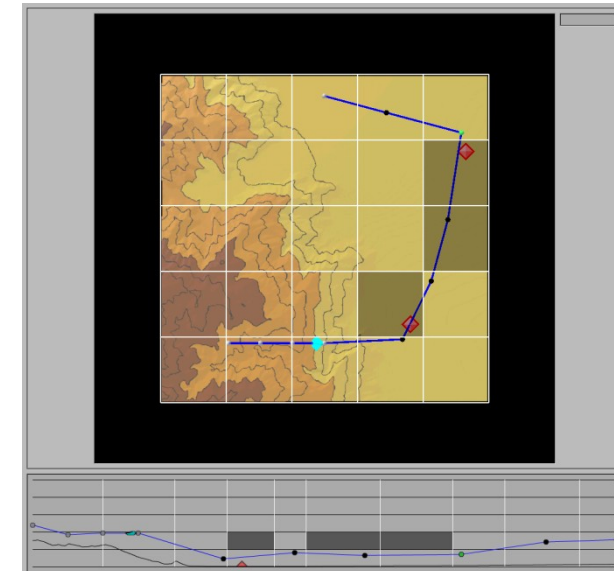
Route



Compromised route

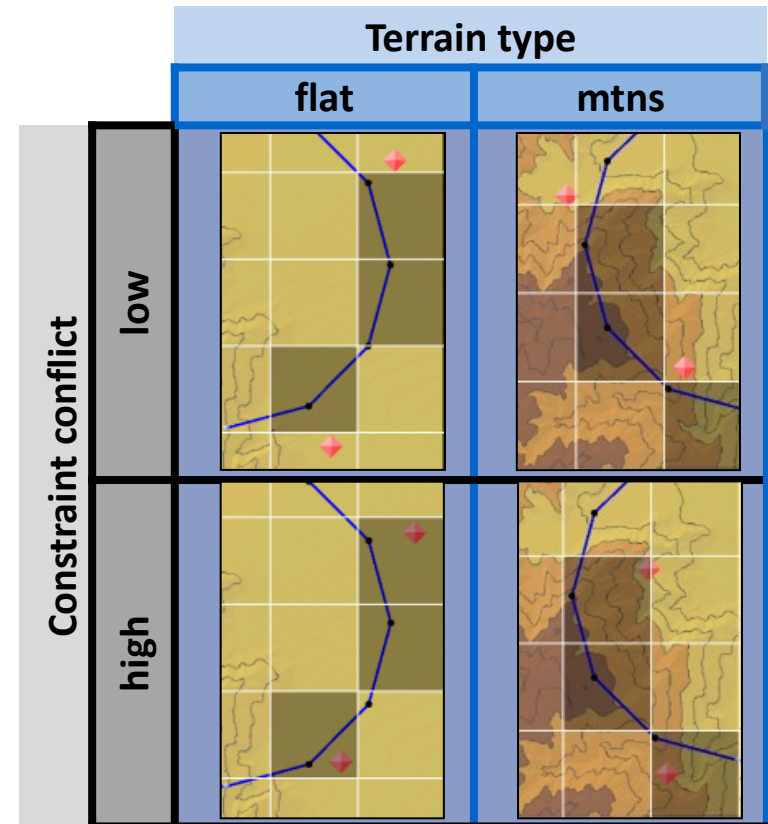


Fixed route



Exp 1: 3D replanning constraints

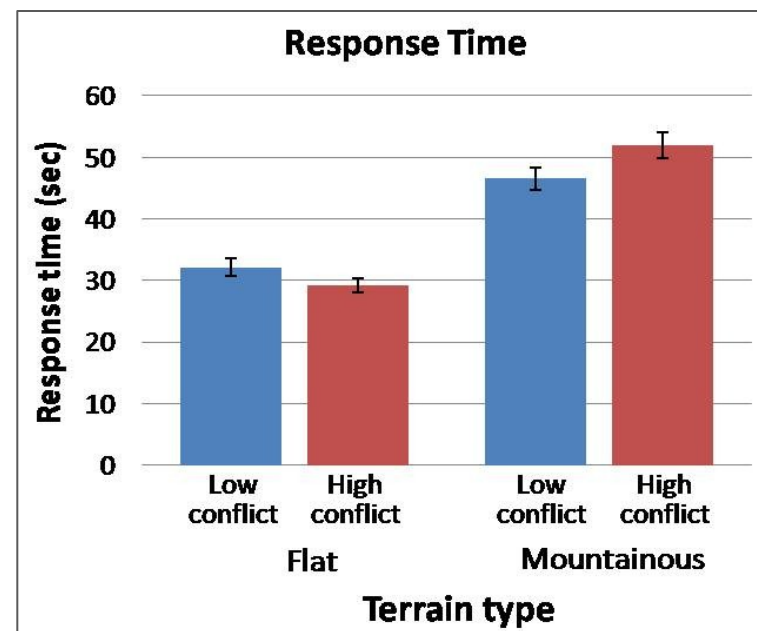
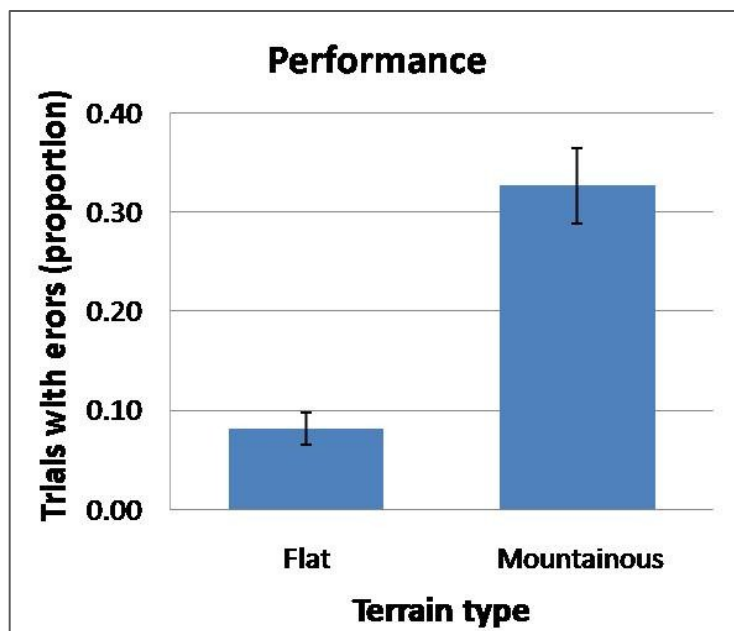
- Independent variables:
 - **Terrain:** flat, mountainous
 - **Constraint conflict:** high, low
- Replanning performance metrics
 - Operator efficiency
 - » Replanning RT
 - » Replanning movements
 - Mission success
 - » Accuracy (general)
 - » Violation types (specific)
 - Route efficiency
 - » Route length



Exp 1: 3D replanning constraints

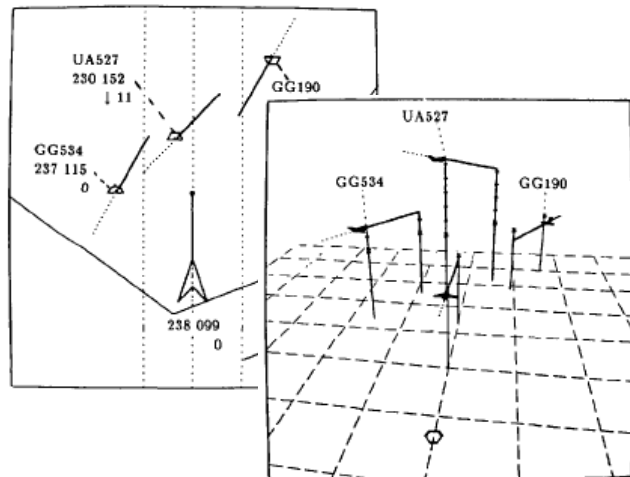
• Results

- Lower mission success in mountainous terrain (accuracy)
- Lower mission success for targets, then airspace, then terrain (violation types – specific)
- Lower operator efficiency in mountainous terrain, especially for high conflict (replanning RT and movements)

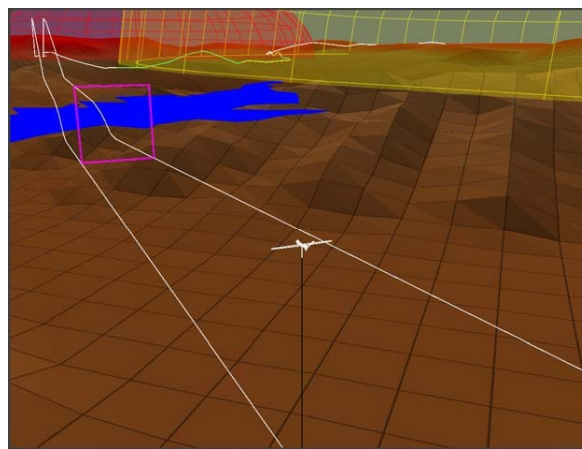


Design new visualizations for replanning

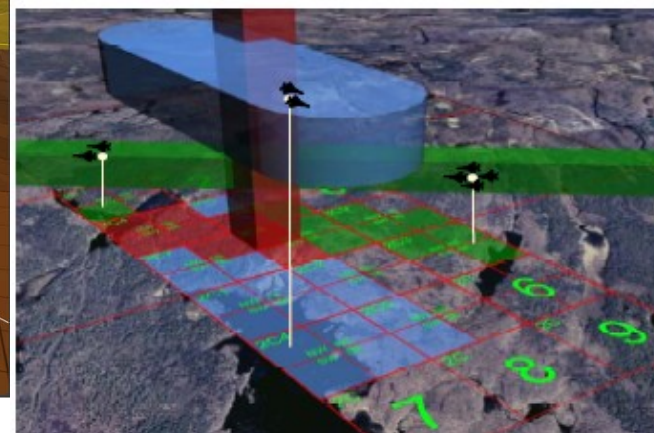
- Reviewed previous approaches for displaying scenes and attributes (including aviation, ATC, synthetic vision)



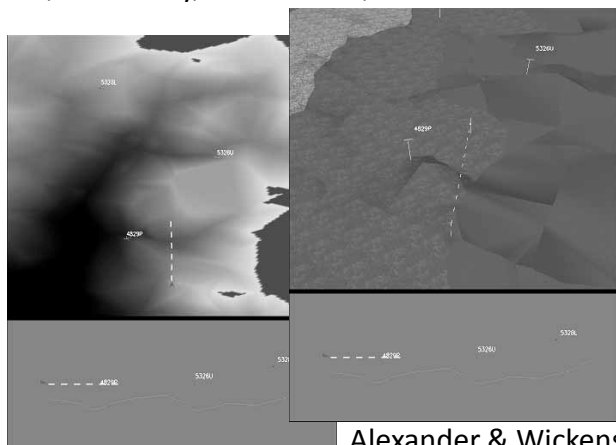
Ellis, McGreevy, & Hitchcock, 1987



Tadema, Koeners, & Theunissen, 2006



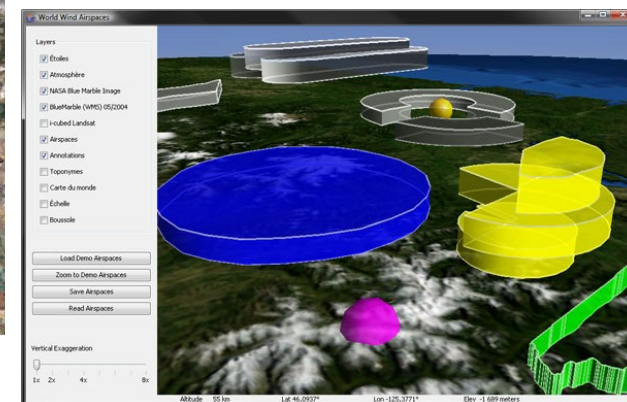
Griffith et al., 2006



Alexander & Wickens, 2004



<http://interactive.usc.edu>



<http://www.alpix.com>

Display feature pro-con analysis

3D ground ref

Terrain

Altitude coding

Scene projection

Airspace / restricted regions

Route

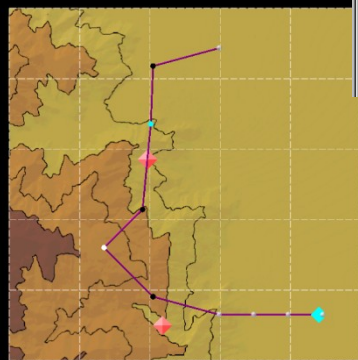
Approach objects

| | Drop lines | Both drop shadows and lines | Lat-long lines | | Achromatic shading | Achromatic shading + topography | Achromatic topography shading | Topo contour map | Solid fill stylized mesh | | Actual altitude | Rendered objects with no explicit altitude coding | Digital altitude readout (continuously available or on demand) | Destruction of object to corresponding top shadow distance | Color |
|-----------------|--|--|--|------|-------------------------|---------------------------------|-------------------------------|-------------------------|--------------------------|-------------------------|-------------------------|---|--|--|-------------------------|
| Example display | None (not used any) | None (not used any) | None (not used any) | None | PVC | 2D Shading, 2002 | 2D Shading, 2002 | PVC | None (not used any) | None (not used any) | 2D style, 2D | 2D style, 2D | 2D style, 2D | 2D style, 2D | 2D style, 2D |
| Pros | Increases vertical level path of suspended object in map | Increases vertical level path of suspended object in map | Increases vertical level path of suspended object in map | None | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection |
| Cons | Increases vertical level path of suspended object in map | Increases vertical level path of suspended object in map | Increases vertical level path of suspended object in map | None | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection | Damage plane projection |

Design of new display visualizations

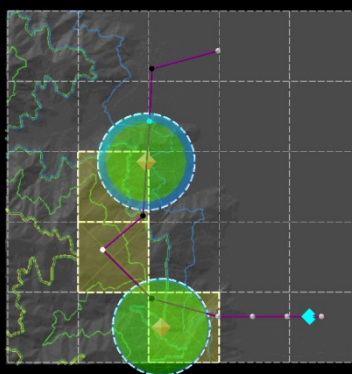
- Informed by
 - Replanning task and display requirements from CTA and taxonomy
 - Display feature pro-con analysis
 - ONR-sponsored PVC project, framework (Smallman, St. John, et al., 1998-2008)
- Constrained by experiment comparison

Baseline 2D



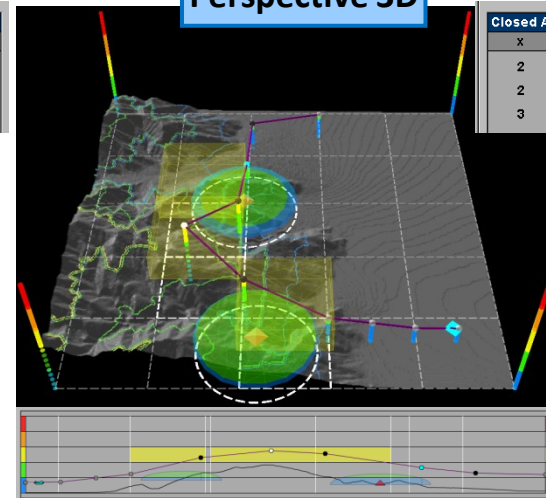
| Closed Airspace Cubes | | |
|-----------------------|---|---|
| x | y | z |
| 2 | 2 | 3 |
| 2 | 3 | 3 |
| 3 | 1 | 3 |

Augmented 2D



| Closed Airspace Cubes | | |
|-----------------------|---|---|
| x | y | z |
| 2 | 2 | 3 |
| 2 | 3 | 3 |
| 3 | 1 | 3 |

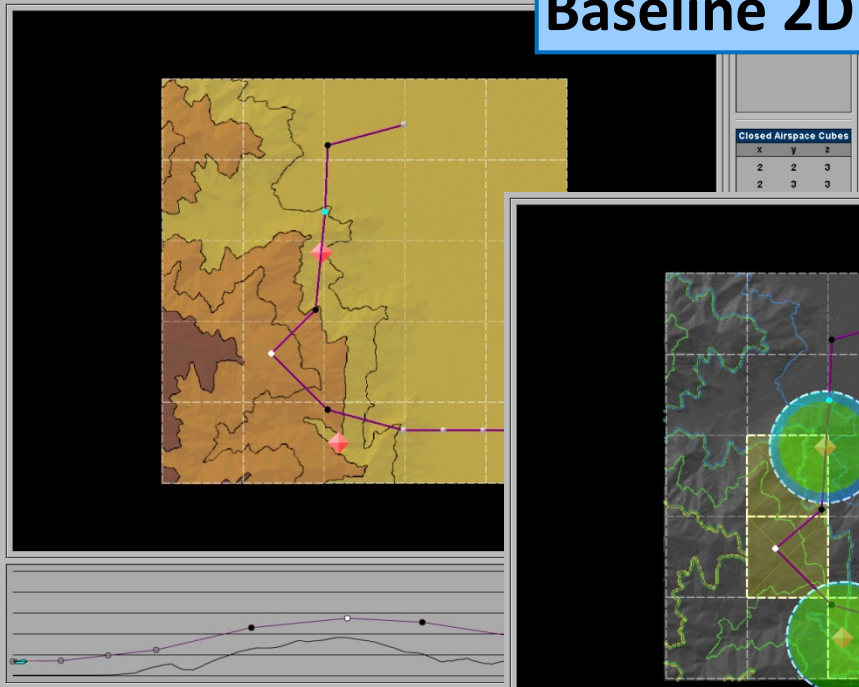
Perspective 3D



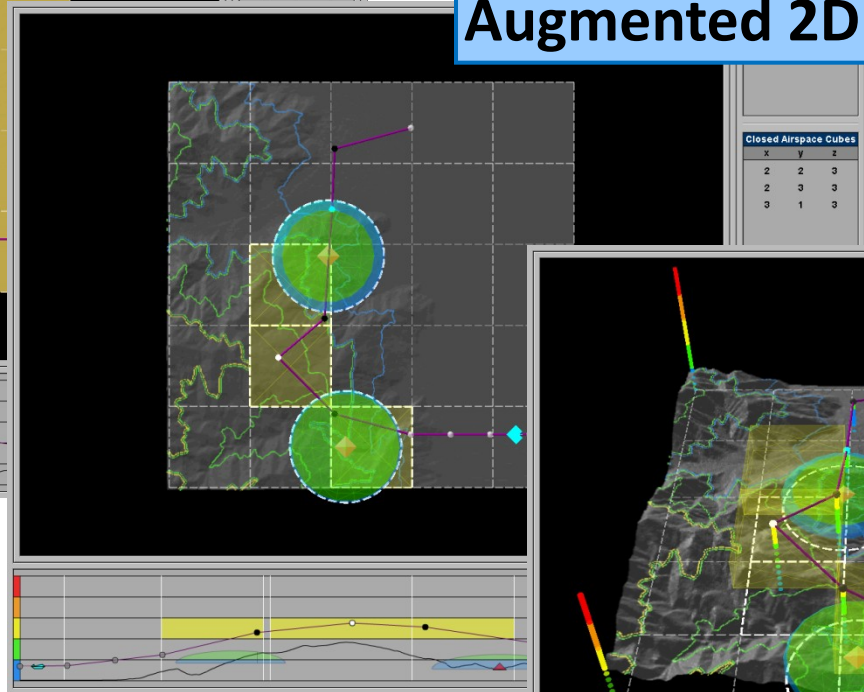
| Closed Airspace Cubes | | |
|-----------------------|---|---|
| x | y | z |
| 2 | 2 | 3 |
| 2 | 3 | 3 |
| 3 | 1 | 3 |

Exp 2 display conditions

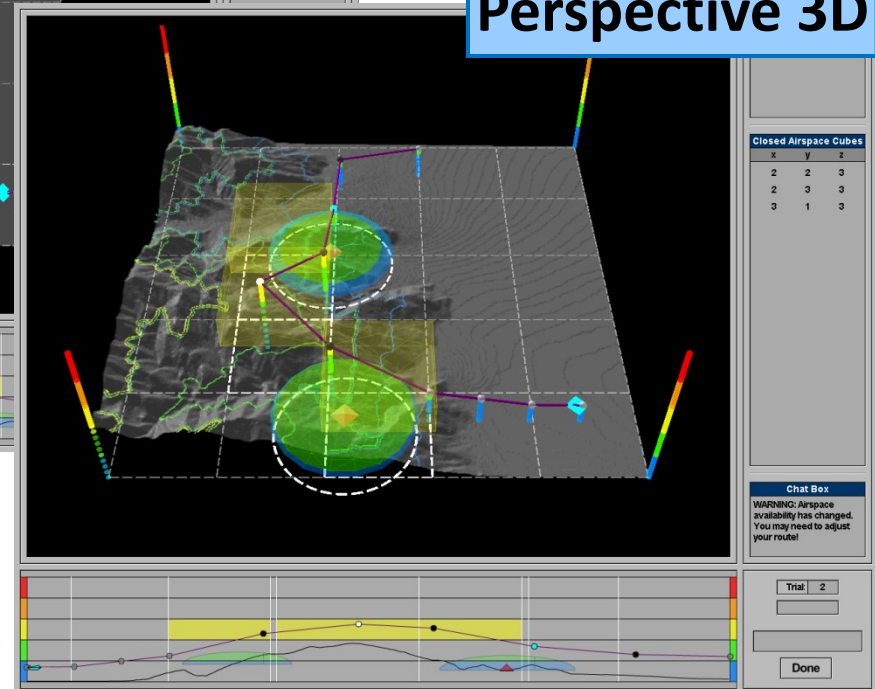
Baseline 2D



Augmented 2D



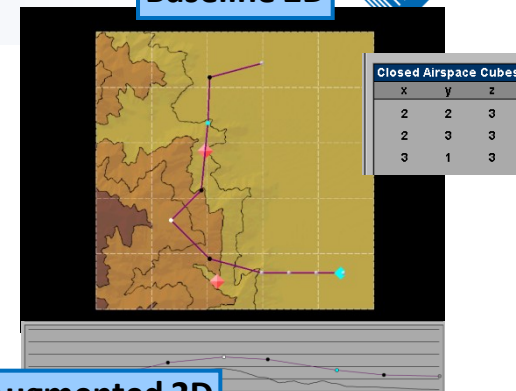
Perspective 3D



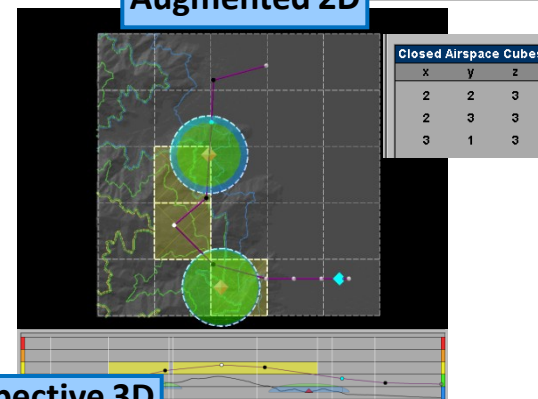
Exp 2: Visualization interventions

- Exp 2 focus
 - Display format
 - Intuitions and preferences
- Repeated Exp 1, + display format
- Replanning performance metrics
 - Operator efficiency
 - » Replanning RT
 - » Replanning movements
 - Mission success
 - » Accuracy (general)
 - » Violation types (specific)
 - Route efficiency
 - » Route length
 - Spatial ability
 - Display intuitions and preference

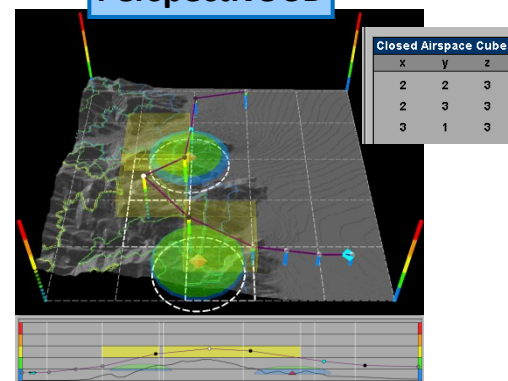
Baseline 2D



Augmented 2D



Perspective 3D

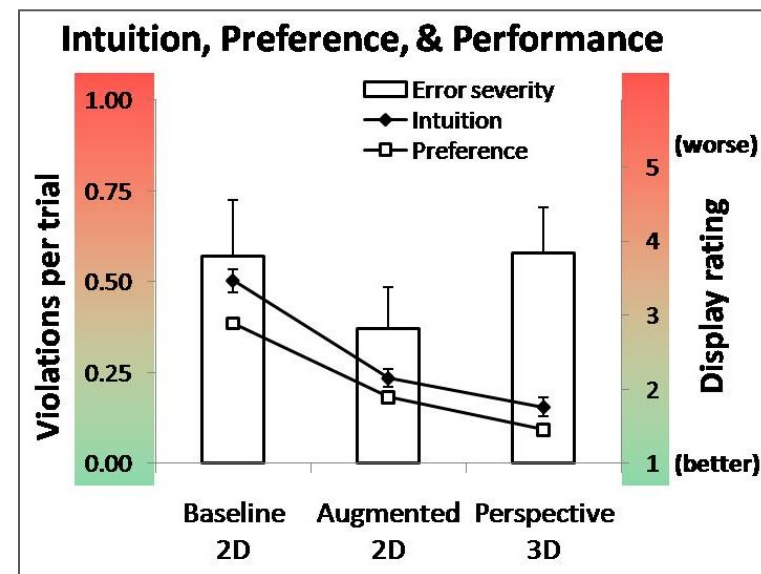
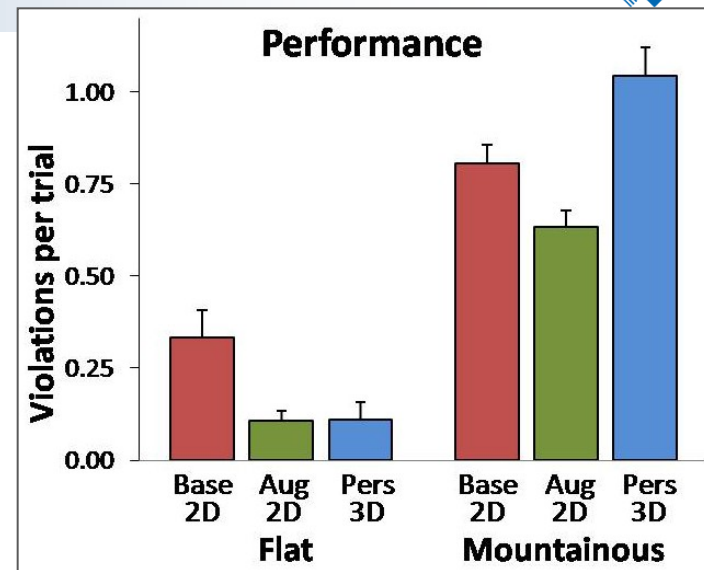


Exp 2: Results

- Display format
 - In mtns, highest mission success for Aug. 2D, lowest for Pers. 3D
 - Doing more with less
 - Perspective 3D ROI questionable

- Intuitions & preference
 - Intuition-performance mismatch
 - Caution against user configuration

- Spatial ability
 - Aug. 2D better performance, without requiring high spatial ability



Summary and application

- Conducted, analyzed, and reported CTA & taxonomy
 - Generalizable to range of UAV environments/missions
 - Informs display design, algorithm requirements (algorithm type, considerations)
- Designed synthetic task to assess replanning performance
 - Adjustable 3D constraint configurations
- Developed operationally-relevant metrics focused on 3D spatial awareness needed for replanning
 - Validated in two controlled performance evaluations (Cook, Smallman, Lacson, & Manes, 2009, 2010)
 - Adaptable for evaluating other C2 systems involving planning, replanning, and routing tasks
- Designed UAV replanning testbed
 - Flexible environment to evaluate display and automation interventions

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