Summary of Progress In The Development Of A Time-to-contact Autorotation Cueing System

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Motivation

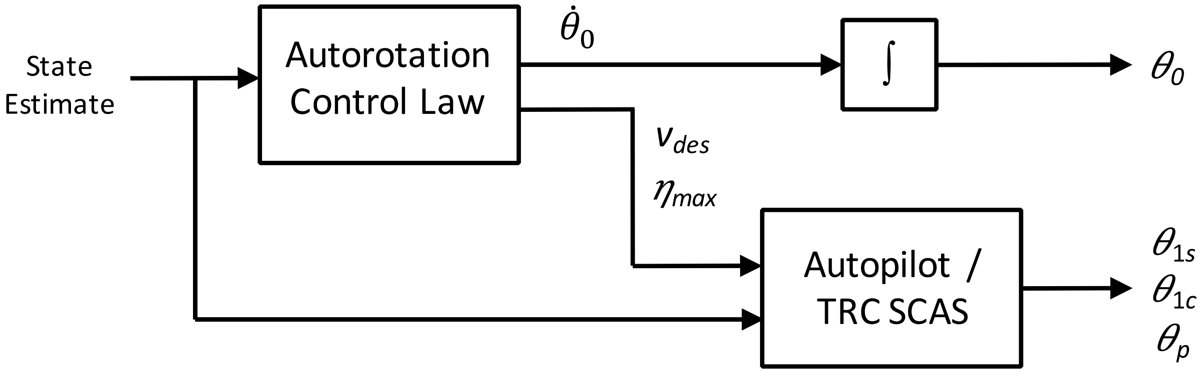
- The autorotation maneuver to land follows a partial or complete engine failure or some other catastrophic failure in a helicopter

https://www.youtube.com/watch?v=BkF4b6OuXJ0

- A successful autorotation outcome requires fast pilot reaction times and appropriate control actions
- This is particularly true for phases close to the ground
- It is a complex and difficult maneuver particularly in degraded visual environments (DVE), night time operations, or low-energy flight conditions
- Even well trained, highly motivated pilots can encounter difficulties
- Can additional cueing be provided to assist a pilot to carry out a successful autorotation maneuver?

Automatic Autorotation Controller

- Georgia Institute of Technology (GT) have previously developed an autonomous autorotation controller[1]
- Controller designed to interface with a standard autopilot or stability and control augmentation system (SCAS) capable of accepting translational rate commands (TRC)



State Estimate

Autorotation Control Law

$\dot{\theta}_0$

$\int$

θ_0

v_{des}

η_{max}

Autopilot / TRC SCAS

θ_{1s}

θ_{1c}

θ_p

- $\dot{\theta}_0$ collective derivative
- V_{des}, forward speed command
- η_{max} = maximum allowable aircraft pitch angle

1. Sunberg, Z., Miller, N., Rogers, J., "A Real-Time Expert Control System for Helicopter Autorotation," Journal of the American Helicopter Society, April 2015

Automatic Autorotation Controller

- Three main phases
    - i. Steady-state
    - ii. Flare
    - iii. Touchdown
- Two additional phases to facilitate transitions between the three main phases
    - i. Pre-flare
    - ii. Landing
- The controller progresses between each phase based on
    - a. Altitude
    - b. Time-to-(ground) contact → **UoL interest**
- If either criteria are satisfied → transition to the next phase
- Phase transitions occur in a fuzzy manner - each phase has partial authority during the transition.

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Project Overview/Research Questions

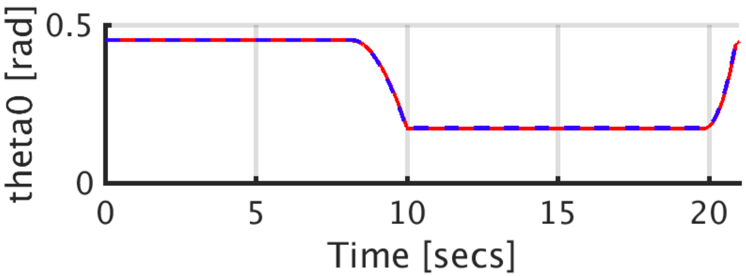
Could the outputs of the GT automated controller be used to cue a pilot in the loop to perform a successful autorotation maneuver?

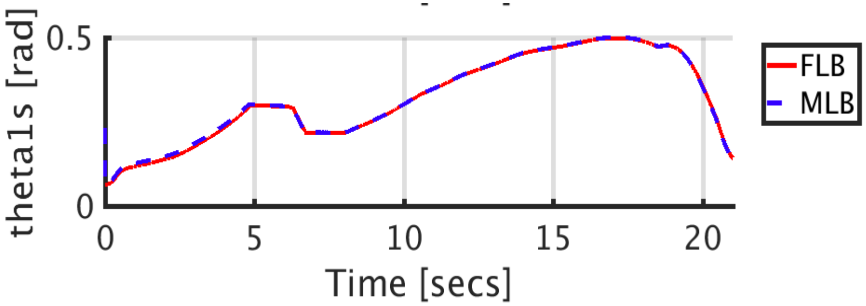
Can time-to-contact be usefully used directly in the control loop?

1. Develop a basic display to provide autorotation cueing to the pilot using the control law as input
2. Integrate the control law into the UoL HELIFLIGHT-R simulation facility
3. Perform simulated flight tests to evaluate the performance of the pilot-in-the-loop autorotation algorithm in both GVE and DVE
4. Develop a time-to-contact based controller to perform to at least the same standard as the ‘conventional’ GT controller?

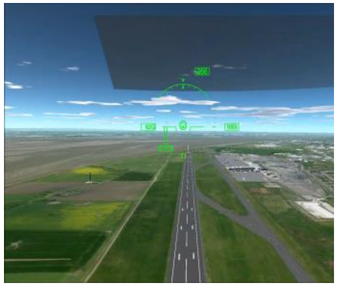
GT Controller Integration at UoL

- GT provided UoL with controller (Simulink)
- UoL implemented this within the FLIGHTLAB Generic Rotorcraft
- Validation & verification showed the implementation to be ‘correct’:





- And the proof of the pudding…



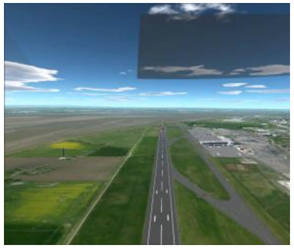
Pilot-in-the-loop Testing

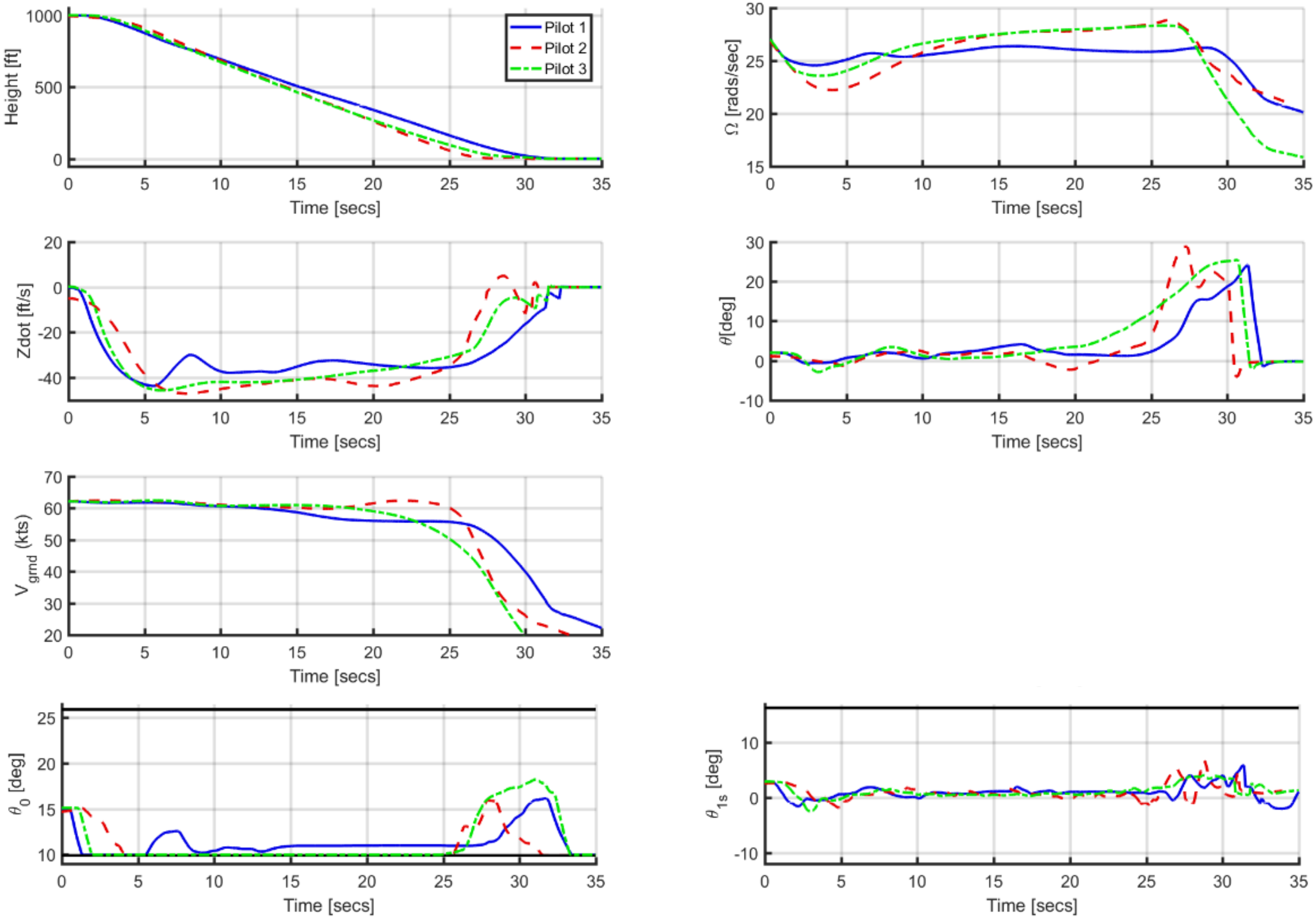
- Test matrix consisting of:
  - 3 engineer pilots with real-world flight experience (2 x fixed- and 1 x rotary-wing)
  - Minimum of 5 autorotation practice maneuvers per test point
  - HUD on/off
  - GVE/DVE
- ‘Success’ criteria

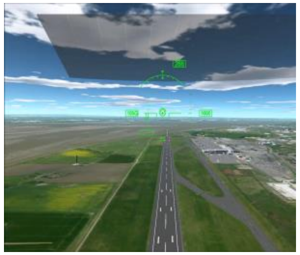
Parameter	Condition for ‘Successful’ landing	Condition for ‘Marginal’ Landing
Pitch Angle. θ	<12°	<20°
Forward Speed, V_{des}	<30 knots	< 60 knots
Vertical Speed, z_dot	< 8 ft/s	<15 ft/s
Pitch Rate, q	-30°/s < q < 20°/s	-50°/s < q < 40°/s

- Some indicative results…

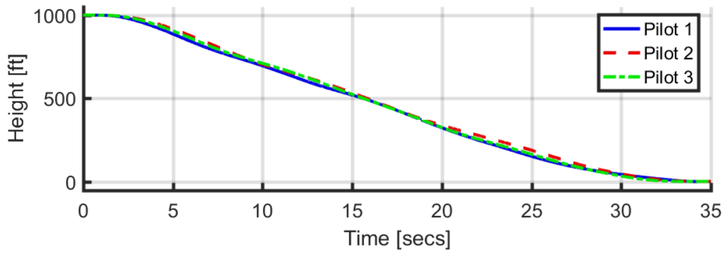
Pilot-in-the-loop Testing – GVE, No HUD

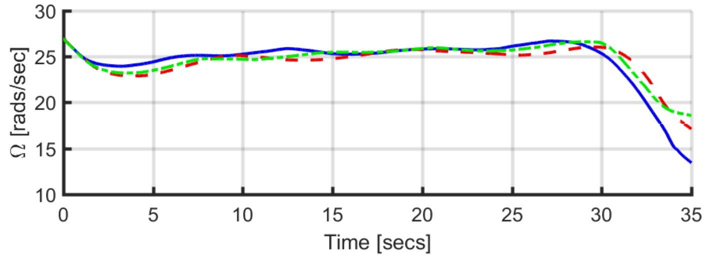


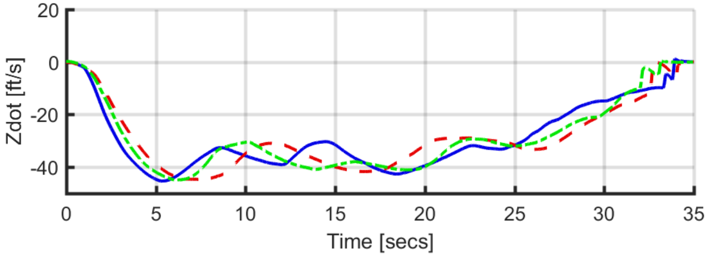


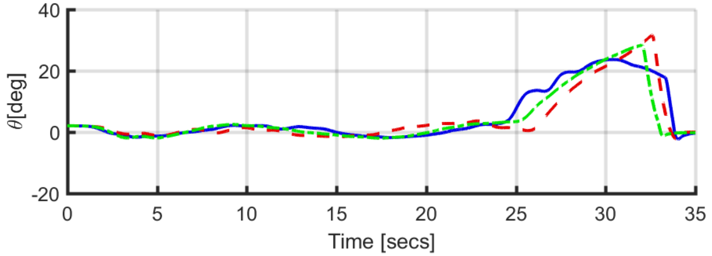


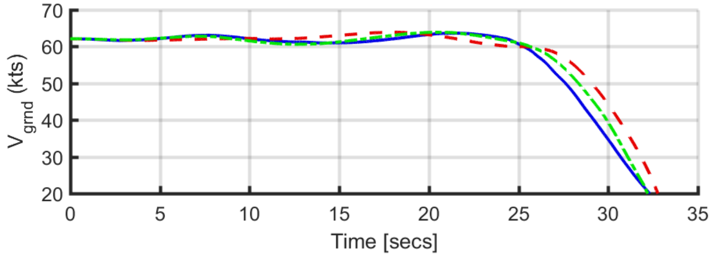
Pilot-in-the-loop Testing – GVE, HUD

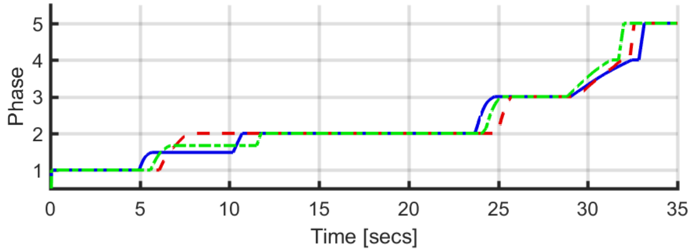


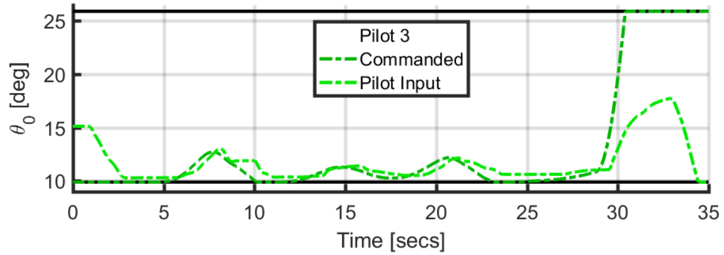


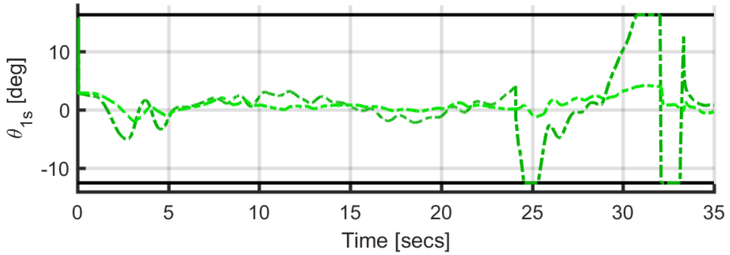












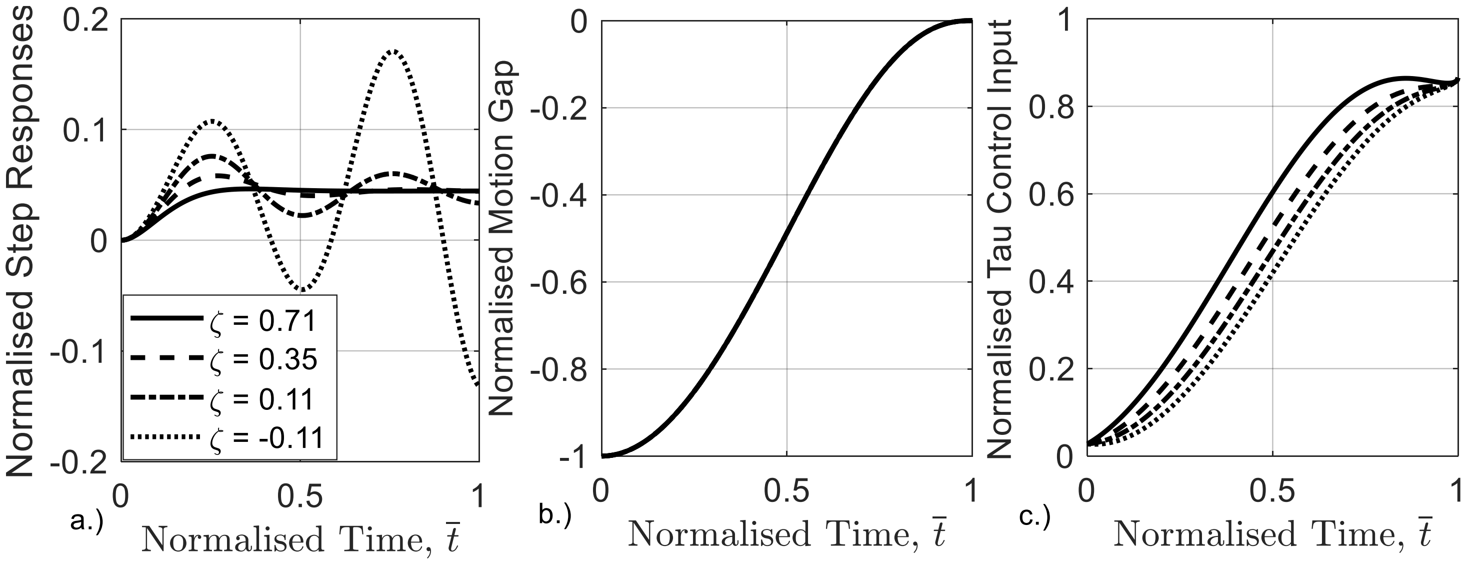
GT Controller Landing Performance Results

- The results for each test point are:

Test Case	Pilot	Ground Speed [knots]	TD Zdot [ft/s]	Pitch Angle [deg]	Pitch Rate [deg/s]
GVE / OFF	1	28	4	8	-24
	2	24	1	-3	12
	3	13	5	11	-35
GVE / ON	1	13	1	-2	6
	2	16	6	-3	-1
	3	17	5	4	18
DVE / ON	1	12	1	-1	8
	2	15	2	-1	18
	3	22	2	-1	19

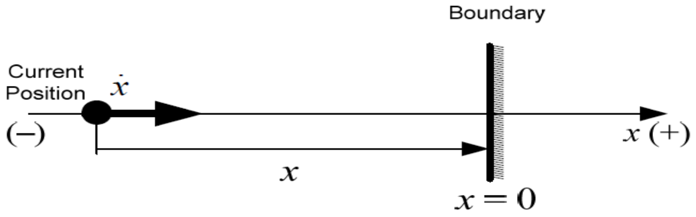
Why Tau?

- Tau can handle variable, even unstable vehicle dynamics
- Behaves like a model inverter without the need for any knowledge of the model
- Can be ‘sensed’ actively or passively



Tau Theory

- Time to contact, τ, is posited to be one of the fundamental ‘optical invariants’ used by an observer to perceive motion



$$\tau(t) = \frac{x(t)}{\dot{x}(t)}$$

→ motion gap

→ gap closure rate

- The term, “motion gap” refers to a perceived difference between the observer’s current and desired target state

Tau Theory

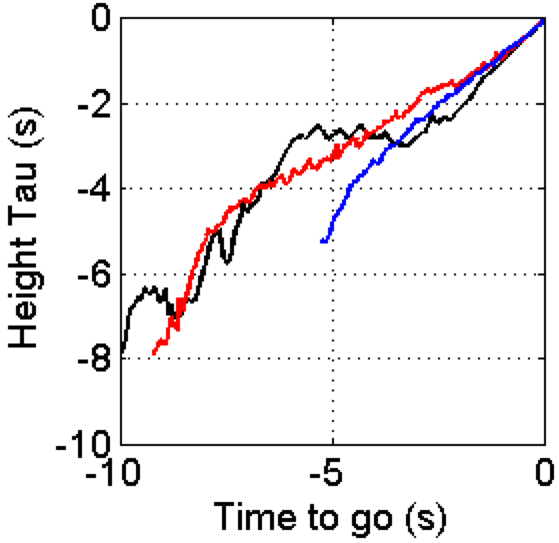
- Tau guidance of the observer's motion is achieved using τ coupling: that is, keeping the tau of one optically available parameter in proportion with the tau of another

- Tau coupling can take two forms: ***extrinsic*** ('x' and 'y' are physically observable) or ***intrinsic*** ('x' is physically observable whereas 'y' is generated by the actor's central nervous system, the so called ***motion guides***)

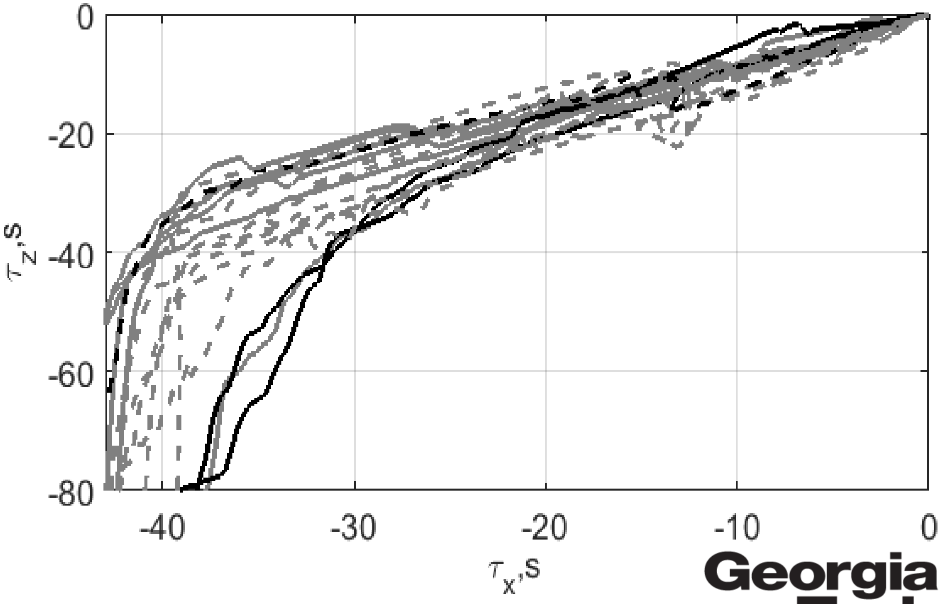
- Another coherent tau-based guidance strategy is to keep the rate of change of tau of the motion-gap constant

Tau Theory

- Fixed-wing flare manoeuvres described by 2 different constant tau-dot-height profiles

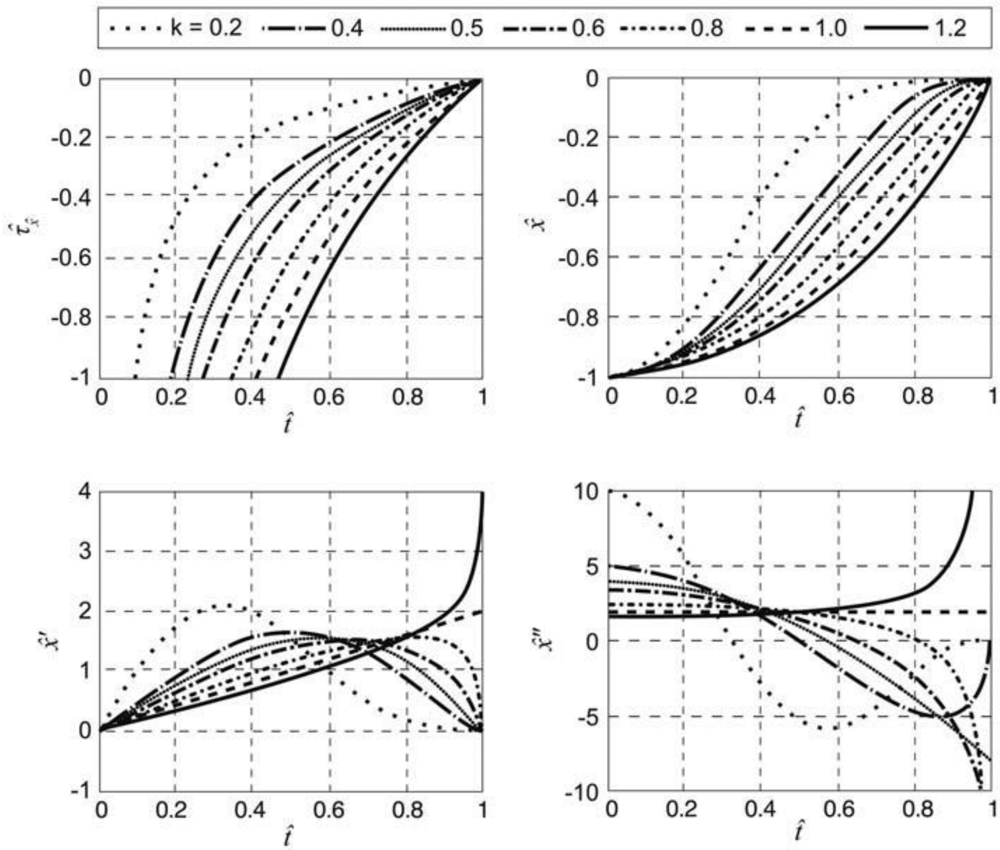


- Personal aerial vehicle approach to hover described by extrinsic coupling of taus of longitudinal distance and vertical distance to final hover position



Tau Theory and the Tau Guide

Constant Acceleration Tau Guide



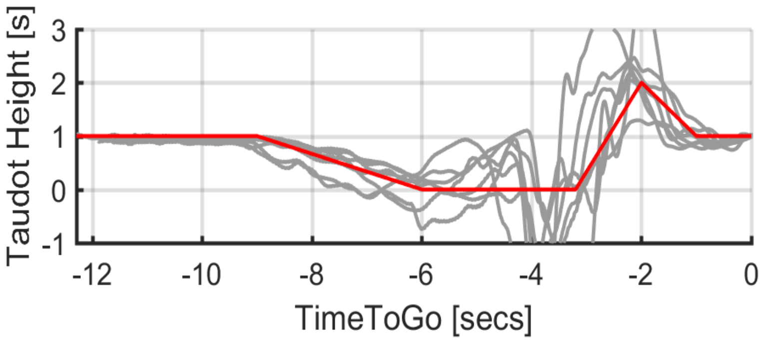
Motion τ, gap distance, closure rate and acceleration when following a constant acceleration guide such that $\tau_x = k\tau_g$.

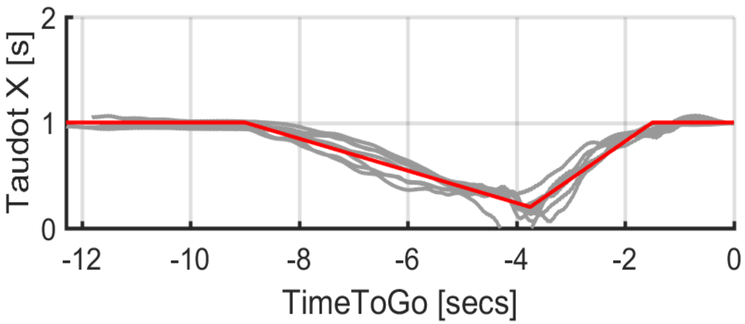
“^”, the dressing indicates that the variables are normalized by total time, T.

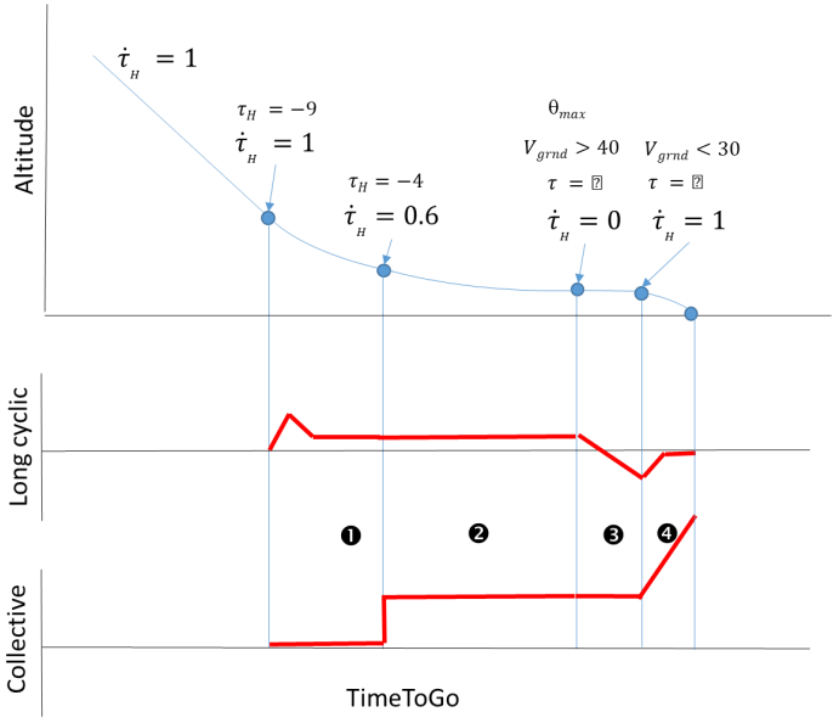
Flight-test Strategies

- Flight test and simulated flight test autorotation manoeuvres were analysed
- Strategies using tau derivatives ($\dot{\tau}$,vertical height and longitudinal distance) across 4 different flight phases of the autorotation manoeuvre were identified
- A new autorotation control algorithm based on the tau-guidance strategy used by pilots was developed
- PID tracking controllers implemented to track $\dot{\tau}$ targets in each phase

Flight-test Strategies

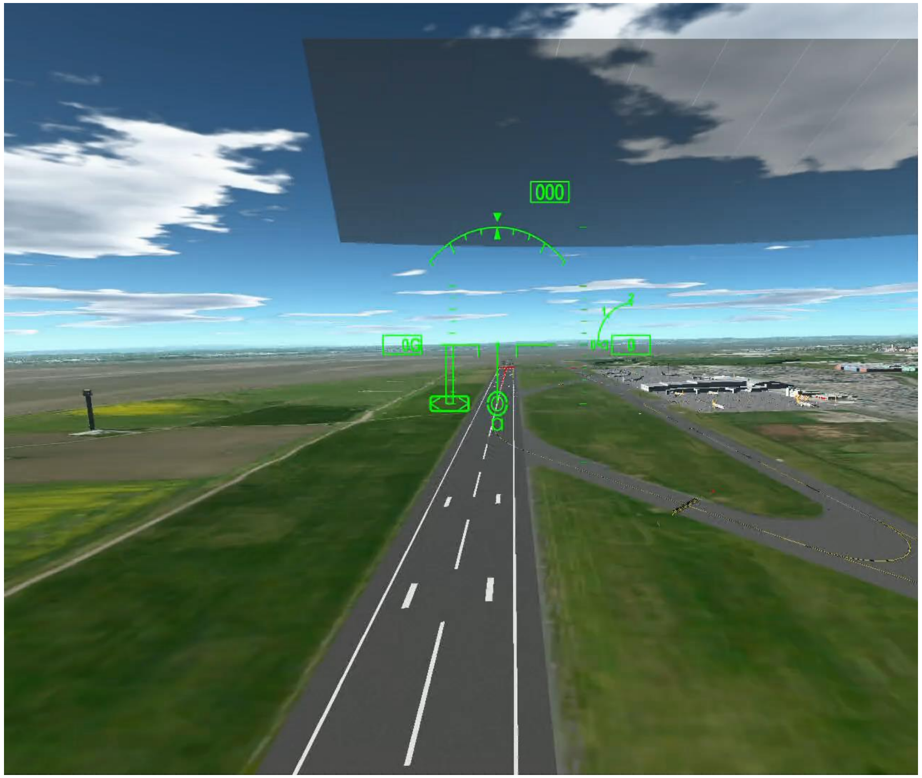






Phase	Name	Longitudinal Cyclic	Collective Pitch
1	Flare	$\dot{\tau}_H$ (=0.6)	Not used
2	Reduce IAS	$\dot{\tau}_X$(=0.1)	$\dot{\tau}_H$(=0.1)
3	Reduce Pitch	Reduce pitch angle	Maintain
4	Land	Maintain pitch angle	(when Vgrnd <30ftsec, Vzi > -8ft/sec, theta <10 deg)

Tau Controller Implementation (Auto)



	V_{xf} [ft/sec]	V_{zf} [ft/sec]	Theta [deg]	q [deg/sec]
Desired	< 30	> -8	< 12	-30 <q < 20
Adequate	< 60	> -15	< 20	-50 <q < 40
AAC	**18.2**	**-7.7**	**6.2**	**-2.13**

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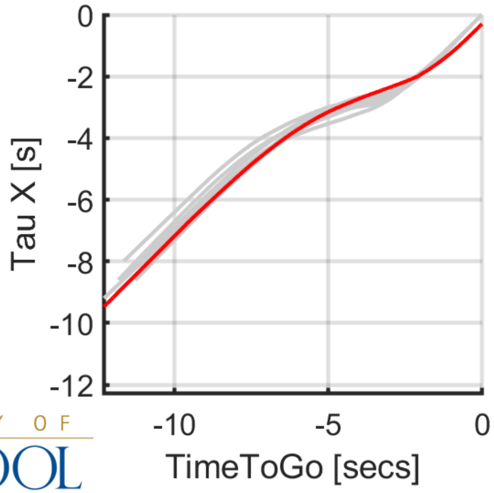
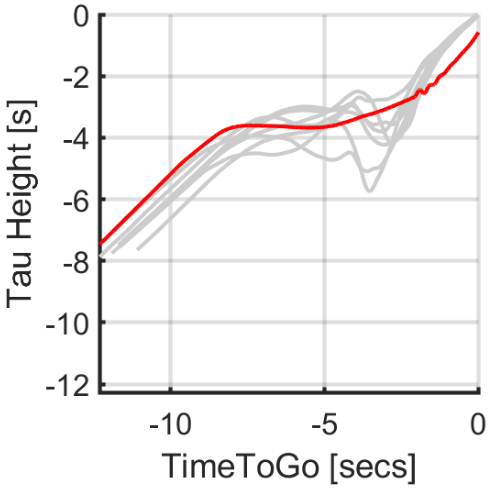
Tau Controller Implementation

- Results of the implemented controller in the tau-domain shown below
- Forward speed and vertical speed at touchdown in acceptable range (~20 kts, 7 ft/s)
- Max pitch angle (30 deg) observed to be excessive
- $\dot{\tau}$ is tracked, albeit imperfectly due to coupled response between pitch, forward speed, vertical speed





Tau Controller Implementation

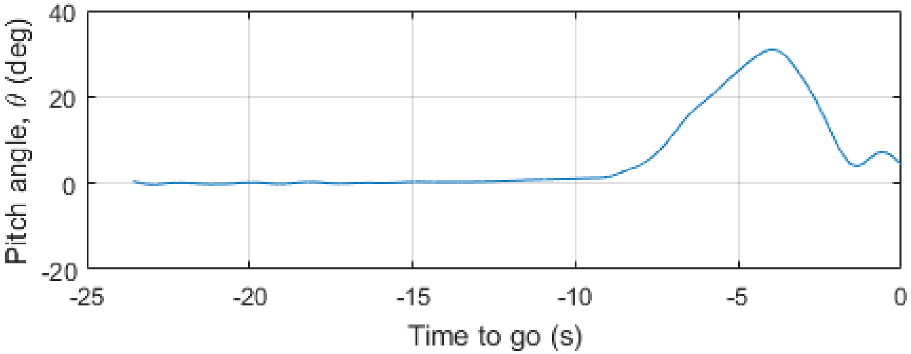
- BUT, collective cue difficult (impossible) to follow
- However, collective cue movement a useful cue for when to start pulling on the collective
- Cyclic cue implementation a little awkward to follow whilst also trying to follow collective cueing if manoeuvre moved too far ‘off plan’ (think patting head and rubbing stomach)
- Pilots unsure about following a display so close to the ground when they would prefer to be looking out of the cockpit window
- Perhaps points towards haptic cueing?

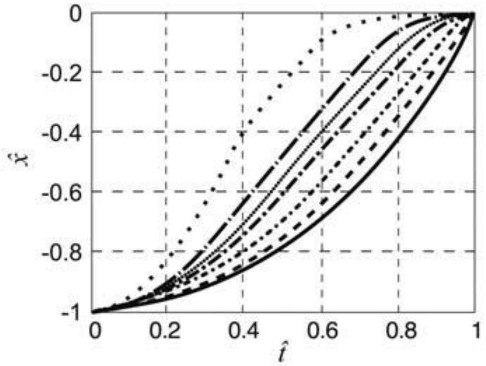
Concluding Remarks

- Two autorotation manoeuvre controllers successfully implemented in real time simulation
- Both provide an automatic autorotation manoeuvre landing capability
- Rudimentary display developed to cue the pilot based upon the outputs of these controllers
- Successful autorotation manoeuvres can be accomplished using these displays
- But this solution does have issues which need to be addressed

Future Work

- More systematic pilot-in-the-loop testing of tau- and conventional-based cueing (display, haptic, {audio?})
- Further explore possible coherent tau motion-gap closures to be used as cue drivers





- Couple this work with the GT work on ‘reachable landing points’ (also tau-based)

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