On-Board AUV Autonomy through Adaptive Fins Control

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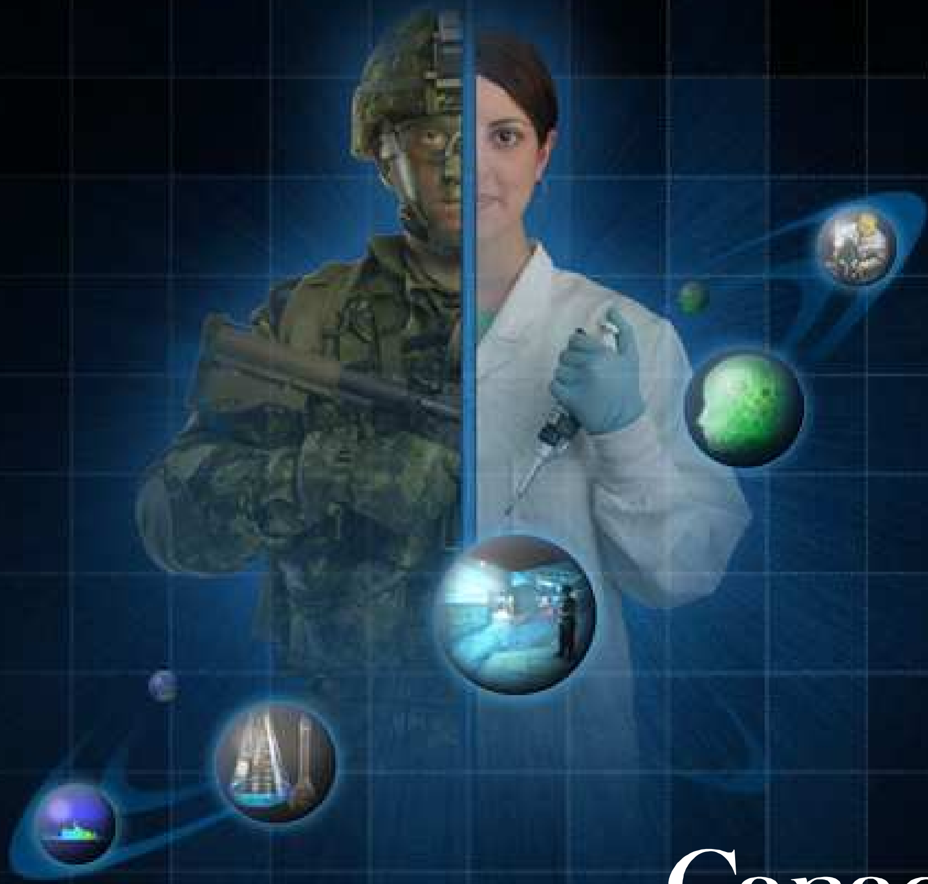

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Outline of Presentation

- Introduction
- Agent for Optimal Fins Control
- Genetic Algorithm Implementation
- Validation
- AUV Response with Jammed Fin
- Current Work
- Concluding Remarks

Motivation for Intelligent Autonomy – 1

- true robotic autonomy is capability to operate long periods without operator intervention
- autonomous underwater vehicles (AUV) of particular interest here
- desirable that AUV has autonomy for decision-making or problem-solving to address *unexpected* vehicle or mission issues
- mission autonomy: adapt mission to unexpected conditions in environment or in-situ intel (e.g. updated CTD measurements) that can be exploited
- vehicle autonomy: increase fault tolerance e.g. a jammed AUV fin
- under-ice autonomy drives requirements for all

Motivation for Intelligent Autonomy – 2

- AUV fins used for altitude, depth, yaw, pitch, and roll control
- a jammed plane's impact on a mission can be severe – ranging from vehicle loss to scuttled mission to compromised control
- if AUV can be recovered the plane / actuator is repaired and the AUV is sent off on mission again
- for AUVs on long deployment a support ship may not be conveniently nearby for this
- no real fail-safes in place to allow the mission to continue in the event of a jammed fin

Motivation for Intelligent Autonomy – 3

an AUV fin can be jammed (underactuated) due to:

- actuator problems
- powering issues
- AUV has collided with something and fin is jammed
- detritus jammed in the actuator

Proposed On-board Autonomy for Jammed AUV Control Fin

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- an on-board re-distribution of control authority can be performed underway to minimize jammed fin impact on a mission
- requires on-board knowledge about the AUV’s dynamics and control
- also requires a means to optimize the control authority
- encapsulated in the form of an on-board knowledge-based agent that is invoked when a jammed fin is detected

Objectives

- study a variety of underactuated fin configurations to assess how the AUV responds given initial gains at mission start
- apply agent to these underactuated conditions to see whether an optimal gain redistribution makes a difference in the AUV's ability to continue a mission or, at least, have enough functionality to transit to a recovery point
- latter is required for a critical failure when it is desirable to recover the vehilcle and the on-board data
- for an under-ice mission, AUV has to be at a precise location for recovery

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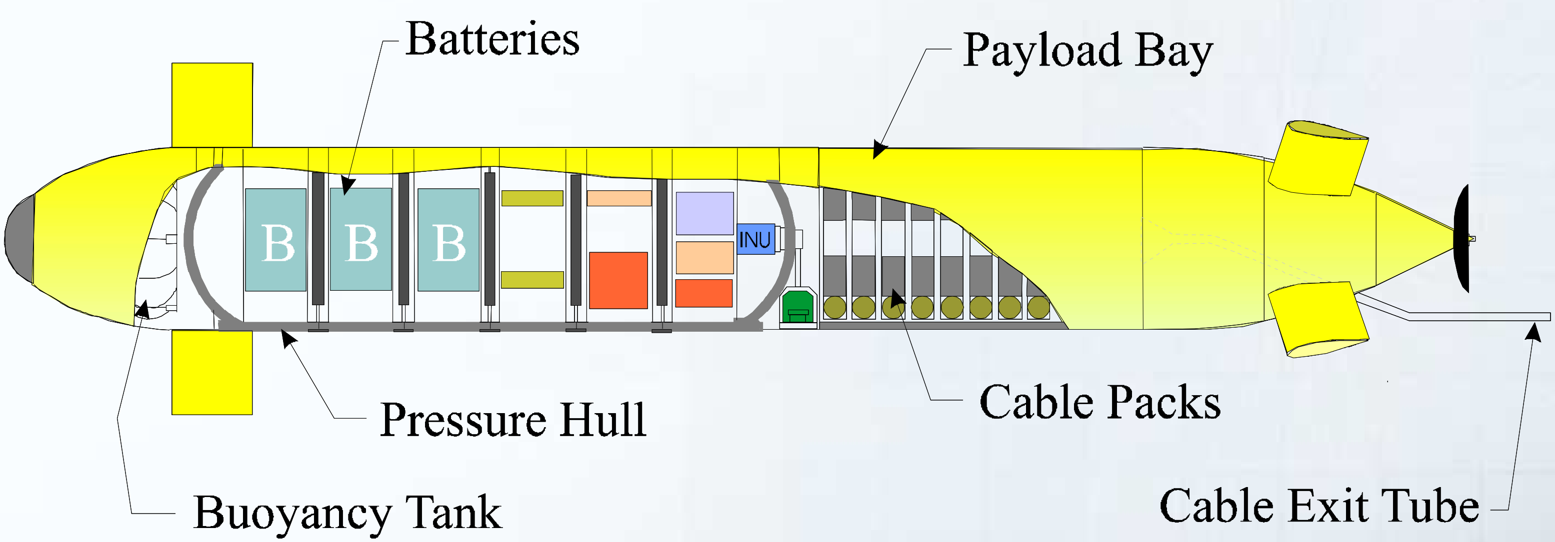
AUV Modelled

- torpedo-shaped geometry (10.7 m long, 8,600 kg displacement)
- + (cruciform) stern fin configuration
- two horizontal bow fins forward of amidship
- control through proportional-integral-differential (PID) control



AUV Dynamics Model

$$X = m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})]$$

$$Y = m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})]$$

$$Z = m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})]$$

$$K = I_x \dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I$$
$$+ m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp = ur)]$$

$$M = I_y \dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I$$
$$+ m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} + uq + vp)]$$

$$N = I_z \dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I$$
$$+ m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)]$$

$$X = -\frac{1}{2}\rho l^4[X_{pp}p^2 + X_{rr}r^2 + X_{qq}q^2 + X_{q|q|}q\,|\,q\,|] + \frac{1}{2}\rho l^3 [X_{\dot{u}}\dot{u} + X_{\dot{v}}\dot{v} + X_{\dot{w}}\dot{w}] + \frac{1}{2}\rho l^4[X_{\dot{p}}\dot{p} + X_{\dot{q}}\dot{q} + X_{\dot{r}}\dot{r}] + \frac{1}{2}\rho l^3 [X_{vr}vr + X_{wq}wq] + \frac{1}{2}\rho l^2[X_{uu}u^2 + X_{vv}v^2 + X_{ww}w^2 + X_{\delta r\delta r}u^2(\delta r)^2 + \frac{1}{2}(X_{\delta b\delta b}u^2(\delta_{bp}{}^2 + \delta_{bs}{}^2) + \frac{1}{2}(X_{\delta s\delta s}u^2(\delta_{sp}{}^2 + \delta_{ss}{}^2) + X_{prop}] + (W - B)\sin\theta$$

- X, Y, and Z are external forces due to added mass, hydrodynamics, statics, and control fins
- control fin damping, natural frequency, and rates are described with a 2nd order model as part of fins' response to commanded deflections

$$[\delta_{bp}, \delta_{bs}, \delta_{sp}, \delta_{ss}, \delta_r]$$

AUV Control Model

- + tail fin configuration chosen since it decouples control of the vertical and horizontal degrees of motions – simplifies analysis
- horizontal fins could be for pitch (θ), roll (ϕ), or depth (Z) control – located close to hydrodynamic center
- yaw / heading (ψ) control achieved through vertical plane stern fins
- fins under closed-loop PID control

$$\delta = \begin{bmatrix}\delta_{bs}\\ \delta_{bp}\\ \delta_{ss}\\ \delta_{sp}\\ \delta_{r}\end{bmatrix} = \begin{bmatrix} \text{PID GAINS MATRIX} \end{bmatrix} \times \begin{bmatrix}\psi\\ \theta\\ \phi\\ \dot{\psi}\\ \dot{\theta}\\ \dot{\phi}\\ Z\\ \dot{Z}\end{bmatrix}$$

Optimizing Re-distributed Fins Control Authority

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- genetic algorithms (GA) solve problems with objectives functions that are not continuous, differentiable or of a closed tractable form
- GA evaluates solutions based on a full non-linear analysis of AUV dynamics and control in straight and level flight at constant speed and depth once underactuated
- once underactuated, multiple objectives are to continue AUV mission at nominally zero roll and pitch set points and hold depth / altitude

Optimizing Re-distributed Fins Control Authority

- PID gains matrix = **[PID]**, E = evaluation function
- E **([PID])** $\rightarrow [\Delta\theta, \Delta\varphi, \Delta z]$ minimize error in pitch, roll, depth
- f = objective function; implicitly a function of E **([PID])**, i.e.

  $f(E[\mathbf{PID}]) = f([\mathbf{PID}]) = w_1 \times (\Delta\theta) + w_2 \times (\Delta\varphi) + w_3 \times (\Delta z)$

  such that w_1, w_2, and w_3 are relative weights of the errors to obtain a measure of a **[PID]** fitness

- given: function $f : A \rightarrow$ Rn from some set A to real numbers

  find: $[\mathbf{PID}]_o \in A : f([\mathbf{PID}]_o) \leq f([\mathbf{PID}]) \; \exists \; [\mathbf{PID}]$ in A

  where A is the solution space spanned by feasible solutions **[PID]** to f where $[\mathbf{PID}]_o$ is the optimal solution to f

Optimizing with GA

- GA simulates evolution of [PID] solution towards an optimal one where "survival of fittest" wins. Steps here are:

1. initialize a space *A* spanned by a population of acceptable solutions, **[PID]**, by applying *E* (**[PID]**); population sizes > 30 did not yield measurable improvements so 30 used
2. evaluate each solution, perform *f*(**[PID]**) ;
3. select a new population from the old population based on the fitness of the solutions;
4. apply genetic operators such as cross-over and mutations to the new population to create new solutions;
5. evaluate newly-created solutions by applying *f*(**[PID]**), and
6. repeat steps 3 to 6 until the termination criteria which, in this case, are based on the convergence of the fitness values.

Gains Ranges for [PID]

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- ranges imposed to confine agent to prevent agent from searching in regions known to NOT yield solns
- nonlinear dynamics and controls analysis performed a priori to put reasonable bounds on gains to be in correct order of magnitude, regions not searched:
  - gains that saturate the fin
  - bow fins at hydro center therefore bow fins not useful for pitch control; horizontal fins will not contribute to yaw control
  - a jammed fins gains range is constrained to zero

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Validation – Background

- performed against sea trials data collected with DRDC Theseus AUV
- mission was straight and level flight (zero pitch and roll set point) at 2 m/sec and while holding depth
- available experimental attitude and depth data as well as fins' gains **[PID]** for these cases
- solution space, *A*, initialized with a population of 30 solutions
  - weights are assigned $w_{pitch} = 0.2$, $w_{roll} = 0.2$, and $w_{depth} = 0.4$

Comparison with Experimental Values – Unjammed Fin Case

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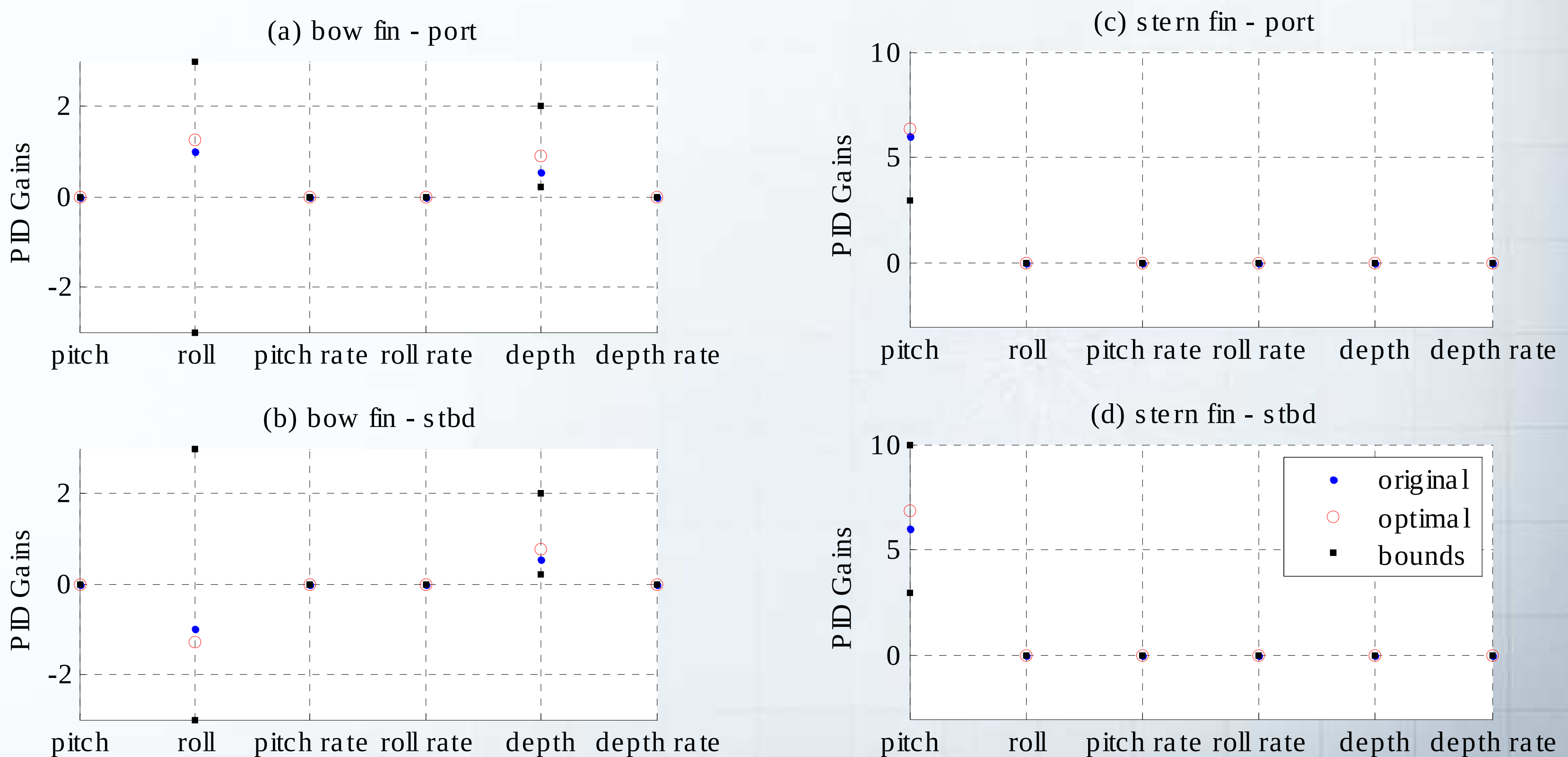
- agent agrees with experimental data that depth and roll-keeping should be in the bow fins (makes sense dynamically)
- port and starboard fins gains for bow fins in roll and stern fins in pitch are close – this is expected but no symmetry conditions were imposed – GA discovered it



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Underactuated AUV

- apply validated agent to jammed (underactuated) fins condition
- a fin is jammed at angles over the full range the fin can deflect (± 24 deg); agent is applied to obtain re-distributed gains matrix **[PID]** ; AUV response in depth, roll, and pitch is compared against that with the original **[PID]** at the beginning of the mission

Underactuated AUV – Jammed Port Bow Fin

- initial gains acceptable for small bow fin jam angles
- agent achieves consistently better pitch (re: bow fins are not contributing to pitch) – optimized stern plane for pitch
- roll is improved consistently – stbd stern fin tasked more to compensate
- clear improvement in depth-keeping; stern fins tasked more and stbd bow fin compensating more – descent in water column is slowed

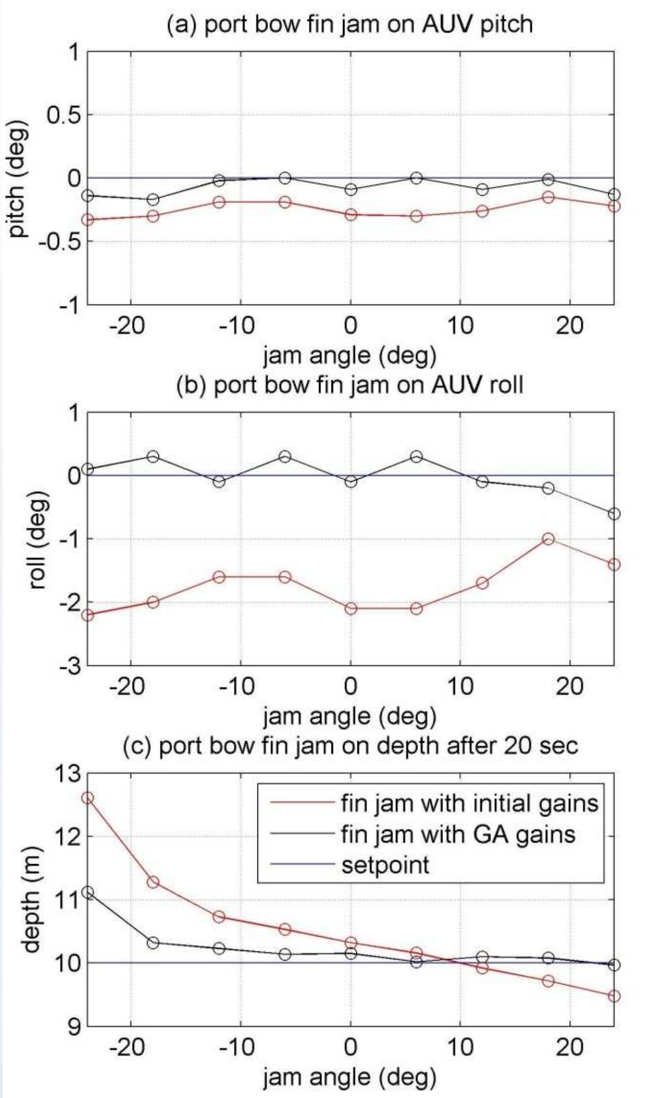

TABLE I: AUV depth rate (m/s) with a bow fin jam

bow fin jam angle	without agent	with agent
-12	0.09	0.003
-18	0.18	0.07
-24	0.41	0.13

Underactuated AUV – Jammed Port Stern Fin

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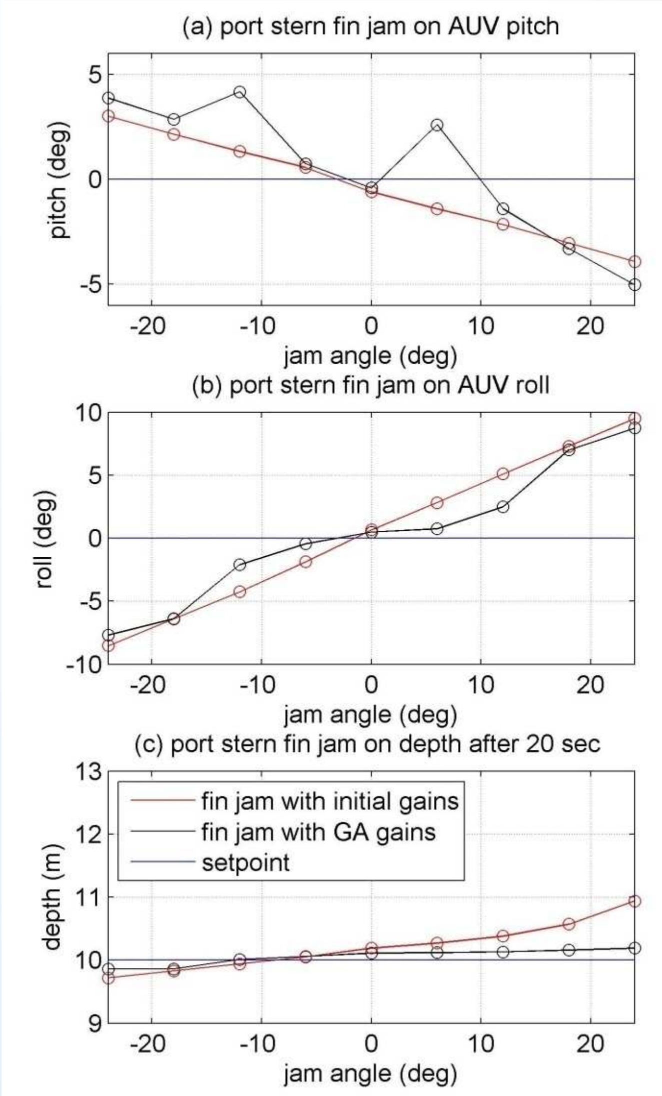
- a jammed stern fin is more critical than a jammed bow fin
- most depth and roll-keeping assigned to bow fins
- agent optimal gains preference depth-keeping over roll keeping for bow fins (as they should based on weightings); stern fins will prefer pitch-keeping as they are the only fins that can, effectively
  - consequently, little control authority for roll-keeping leading to high roll angles
- nonetheless, with agent, roll is improved – less so at high angles as expected as the large asymmetrical hydrodynamic forces are now beyond the fins' ability to compensate for

Underactuated AUV – Jammed Port Stern Fin

- since only stern fins can pitch-keep and the bow fins cannot help – large pitch angles seen; agent increases pitch at the cost of lower roll
- depth consistently improved though impact on depth is small (since there are still bow fins)



Other Applications for Agent

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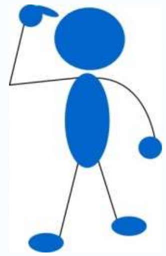
- implement the agent on-board our in-house AUVs
- apply the agent to the case of an AUV that is unexpectedly missing a plane



- apply this agent to AUVs that are towing as the tow can have quite an impact on the AUV heading, pitch, roll, and depth, hrough large incurred tow loads
- improved sea-keeping for AUVs

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Concluding Remarks

- an on-board knowledge-based agent that can autonomously re-distribute control authority in an underactuated AUV – allows an AUV continue a mission and avert a potential vehicle loss
- optimized control authority redistribution is achieved through a genetic algorithm that evaluates the solutions through a nonlinear analysis of the AUV dynamics and control in underactuated configurations
- currently undergoing implementation on-board an AUV
- agent also being evaluated for AUVs that tow, and in navigating sea states

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