THRUSTERS

Optimal Thrust Allocation in DP Systems

Dr. John Leavitt

L-3 Communications Dynamic Positioning and Control Systems

October 7-8, 2008

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Optimal Thrust Allocation in a DP System

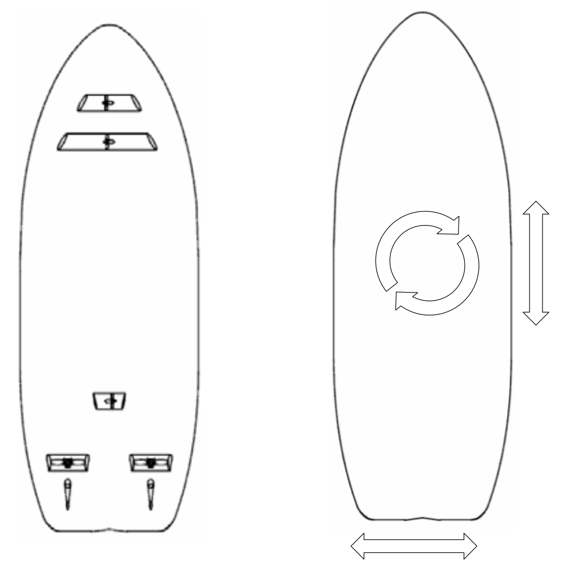
By

Dr. John Leavitt

L-3 Communications DPCS

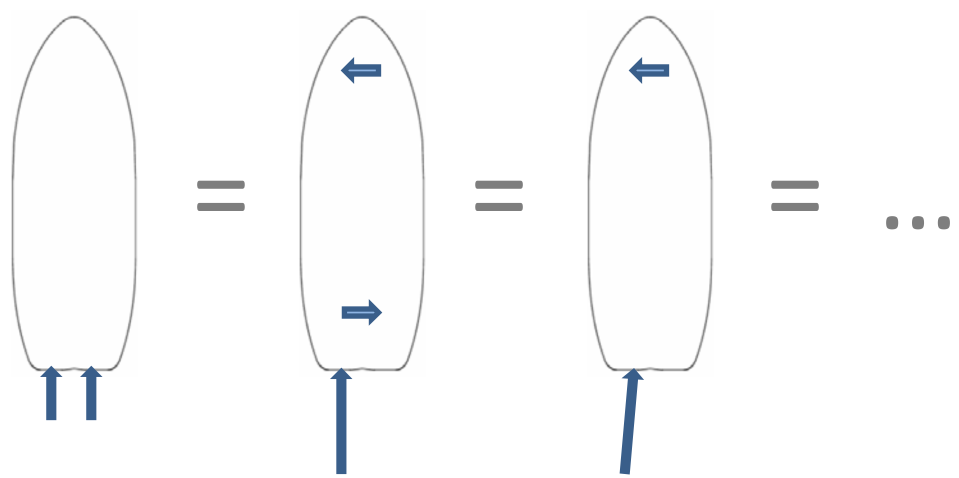
INTRODUCTION

- What is thrust allocation?
- With DP, we seek full control of all 3 DOF
- Due to redundancy requirements, most DP vessels are over-actuated
- Example: 7 actuators > 3 DOF = over-actuated
- overactuated = infinite allocation solutions



7 Actuators

3 Degrees of Freedom (DOF)



INTRODUCTION

• What is optimal thrust allocation?
 -the “best” solution with respect to a number of requirements

General Requirements:
1.Low power
2.Low peak thrust levels
3.Minimize actuator oscillations (e.g. fluttering rudder)
4.Yaw-axis priority

• quantify how poorly an allocation solution meets each requirement

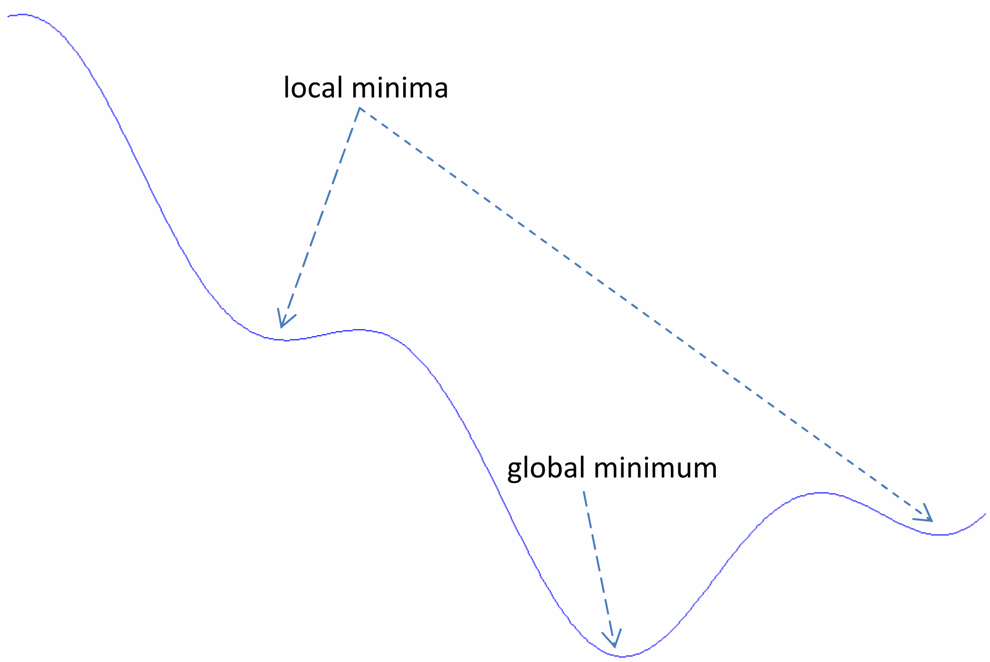
• quantities are weighted and summed, yielding “cost”

• find the solution that minimizes cost, without violating constraints:
 -rate constraints (e.g. slew rate)
 -power limits
 -thrust limits
 -etc.

• problem must be solved once every control cycle!

INTRODUCTION

• quadratic programs, if formulated correctly, can be explicitly and globally solved



THE QUADRATIC PROGRAM

QUADRATIC PROGRAM (QP)

Standard QP

-quadratic cost function J:

$$J(u) = u^T M u + c^T u$$

-linear constraints:

$$Gu \leq w$$

-if M > 0 (all positive eigenvalues) , and J is bounded below, a *unique* global minimum exists

Multi-parametric QP (mp-QP)

-quadratic cost function J, *parameterized* by x

$$J(u) = u^T M u + (x^T F + c^T)u$$

-linear constraints, *parameterized* by x:

$$Gu \leq w + Ex$$

-parameter space (convex polyhedral) defined by:

$$Ax \leq b$$

-if M > 0, and J is bounded below, a unique global minimum exists for any x

-explicit solutions w.r.t. x can be calculated

EXPLICIT SOLUTIONS TO MP-QP

- CR is the parameter space defined by:

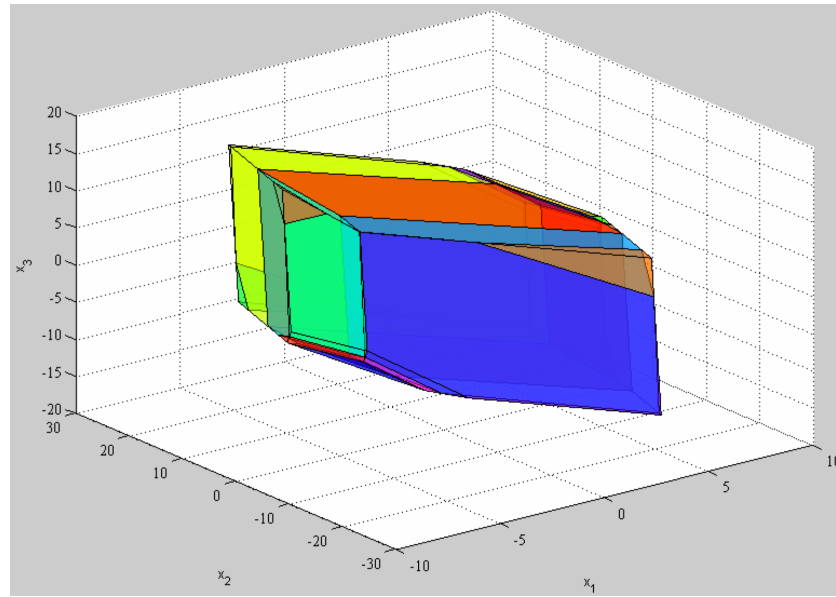
$$CR = \{ x : Ax \le b \} = \cup_{i=1}^{N} CR_i$$

- where the subspace

$$CR_i = \{ x : H^i x \le k^i \}$$

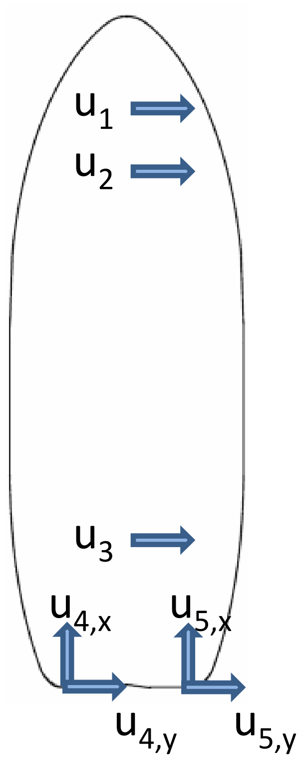
- to implement the solution for a given x, search to find which subspace x belongs to, then calculate:

$$u_* = F^i x + g^i$$

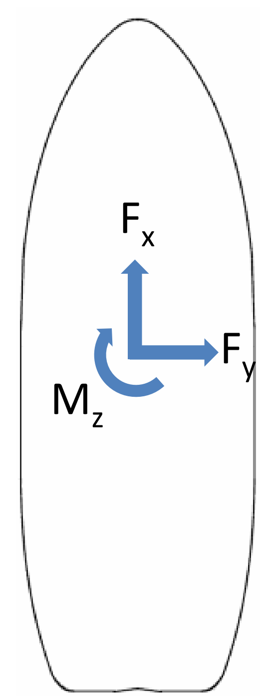


JOHANSEN'S ALLOCATION FORMULATION

- JOHANSEN, T. A., T.P. FUGLSETH, P. TØNDEL, and T.I. FOSSEN. "Optimal Constrained Control Allocation in Marine Surface Vessels with Rudders." *IFAC 6th Conference on Maneuvering and Control of Marine Crafts*, IFAC, 2003, pp. 215–220.



$$B \cdot \begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_{4x} \\ u_{4y} \\ u_{5x} \\ u_{5y} \end{pmatrix} =$$



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- u, "extended thrust" vector

- B, allocation matrix, transforms individual actuator commands to net force and moment

- s, "slack vector" that allows for prioritized cutbacks $s = \tau_c - Bu$

- Cost Function:

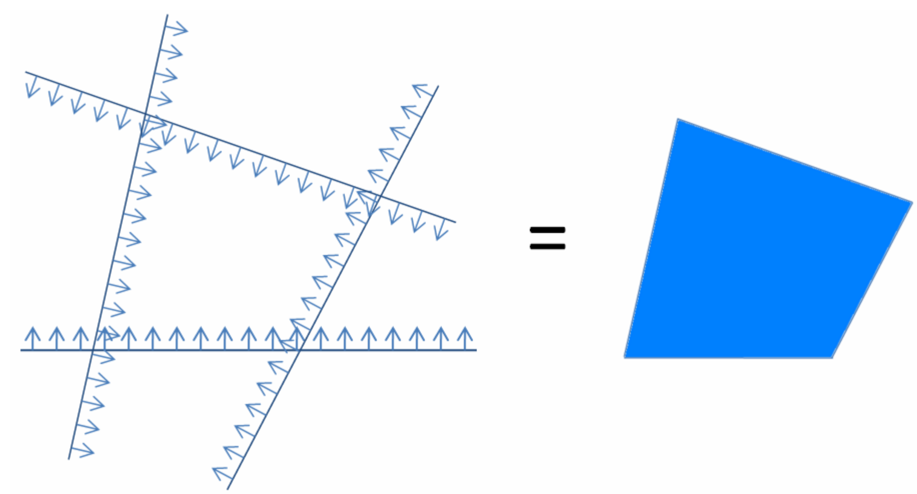
$$J(u,x) \equiv u^T H u + s^T Q s$$

LINEAR CONSTRAINTS, Ax ≤ b

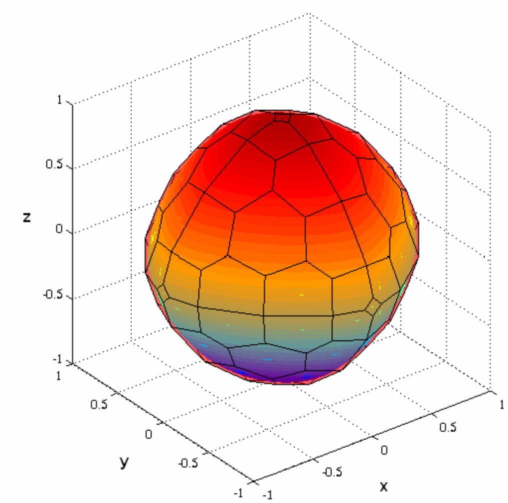
- the above statement is a compact way of writing:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \le b_1 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \le b_m \end{cases}$$

•Example: when n = 2,
we have a convex polygon



- Example: when n = 3,
we have a convex polyhedral



- m is the number of edges, facets, or *hyper-planes* that define the region

ALLOCATION CONSTRAINTS

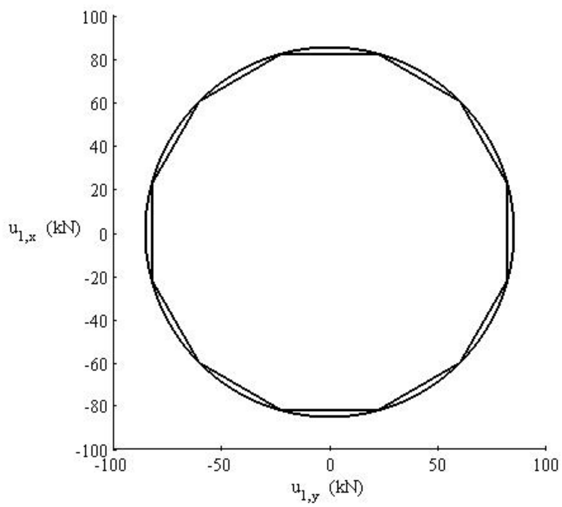
- thrust limits:

  $r^2 = u_x^{\ 2} + u_y^{\ 2} \leq r_{max}^{\ \ 2}$

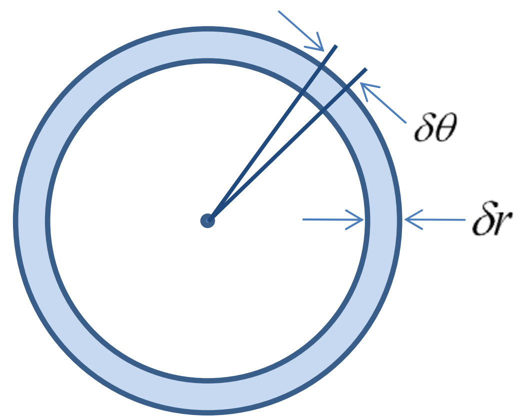
- rate limits:

  $\dot{\theta} \leq \dot{\theta}_{\max}, \quad \dot{r} \leq \dot{r}_{\max}$

- power limits can in some cases be *linearized* as well

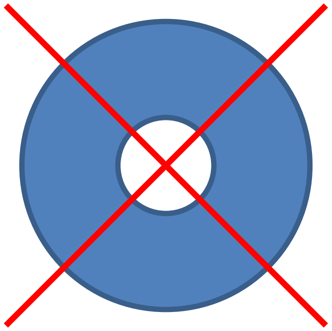


thrust limits for an azimuthing thruster

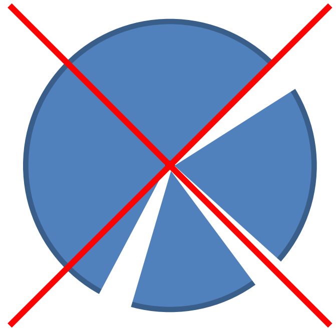


rate limits for an azimuthing thruster

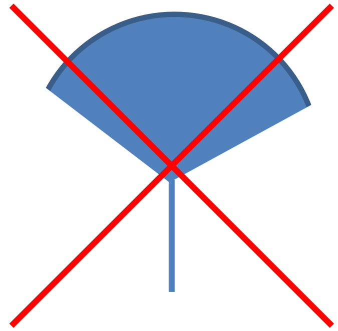
LIMITATIONS OF $Ax \leq b$



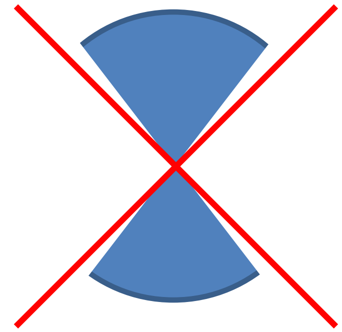
Non-zero Minimum Thrust
(e.g. clutched engine)



Spoil Zones



Rudders



Bidirectional Azis w/
Limited Range of
Motion

- Power limits can only be handled in certain cases

<u>Workarounds</u>

- Rudder thrust regions can be split into two convex regions (see Johansen)

- Spoil zones and bidirectional thrusters can be handled likewise

- Spoil zones aren't configurable when handled this way, and offline computation times are potentially a nightmare

- Non-zero minimum thrust ***cannot*** be handled in QP framework

LIMITATIONS OF A QUADRATIC COST FUNCTION

• neither total power nor peak thrust levels are explicitly minimized (not a real issue).

• no cost can be assigned to rotational motion
  RESULT: flutter, oscillation, hunting, etc.
  WORKAROUND: Johansen’s shifting method, rudders only!

SUMMARY OF MP-QP WEAKNESSES

- azimuthing thrusters will rotate excessively in low sea states
- spoil zones cannot effectively be handled
- non-zero minimum thrust cannot effectively be handled for azimuthing thrusters
- explicit rate limits for azis are not possible
- power limiting can only be handled for simple cases, but with prohibitive offline computation times in a commissioning setting

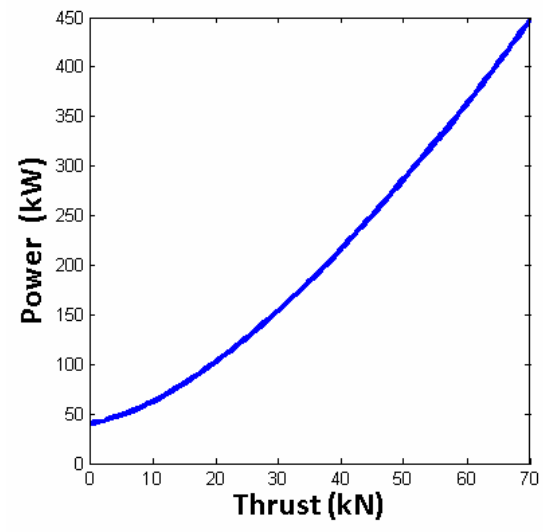
EXAMPLE OF POWER LIMITING USING MP-QP

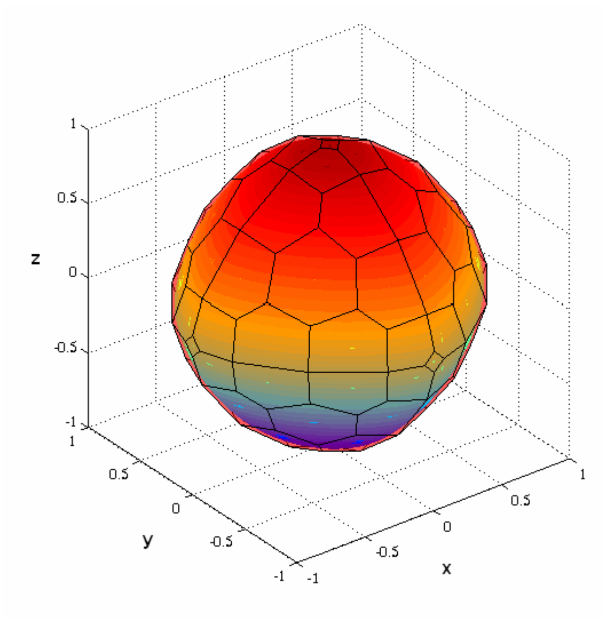
- Approximating power from thrust:

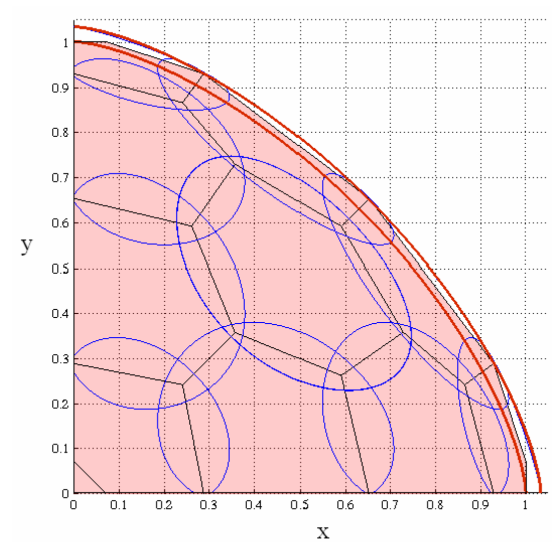
$$P = (P_{\max} - P_{\min})(|T|/T_{\max})^{\eta} + P_{\min}$$

- Example: three thrusters on a power bus

$$\frac{P_{1,\max}}{T_{1,\max}^{1.5}}|T_1|^{1.5} + \frac{P_{2,\max}}{T_{2,\max}^{1.5}}|T_2|^{1.5} + \frac{P_{3,\max}}{T_{3,\max}^{1.5}}|T_3|^{1.5} \le \Psi$$







POWER LIMITING USING MP-QP

• Power limits Ψ can be added to the parameter list x

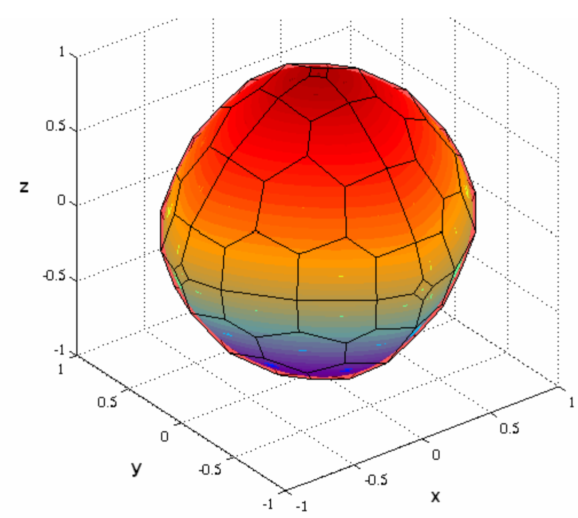
• Polyhedral scales easily using parameterized constraints:

$$Gu \le w + Ex$$

DRAWBACKS

• Offline computation times are prohibitive for even simple cases

• Linearization procedure is difficult for higher dimensions

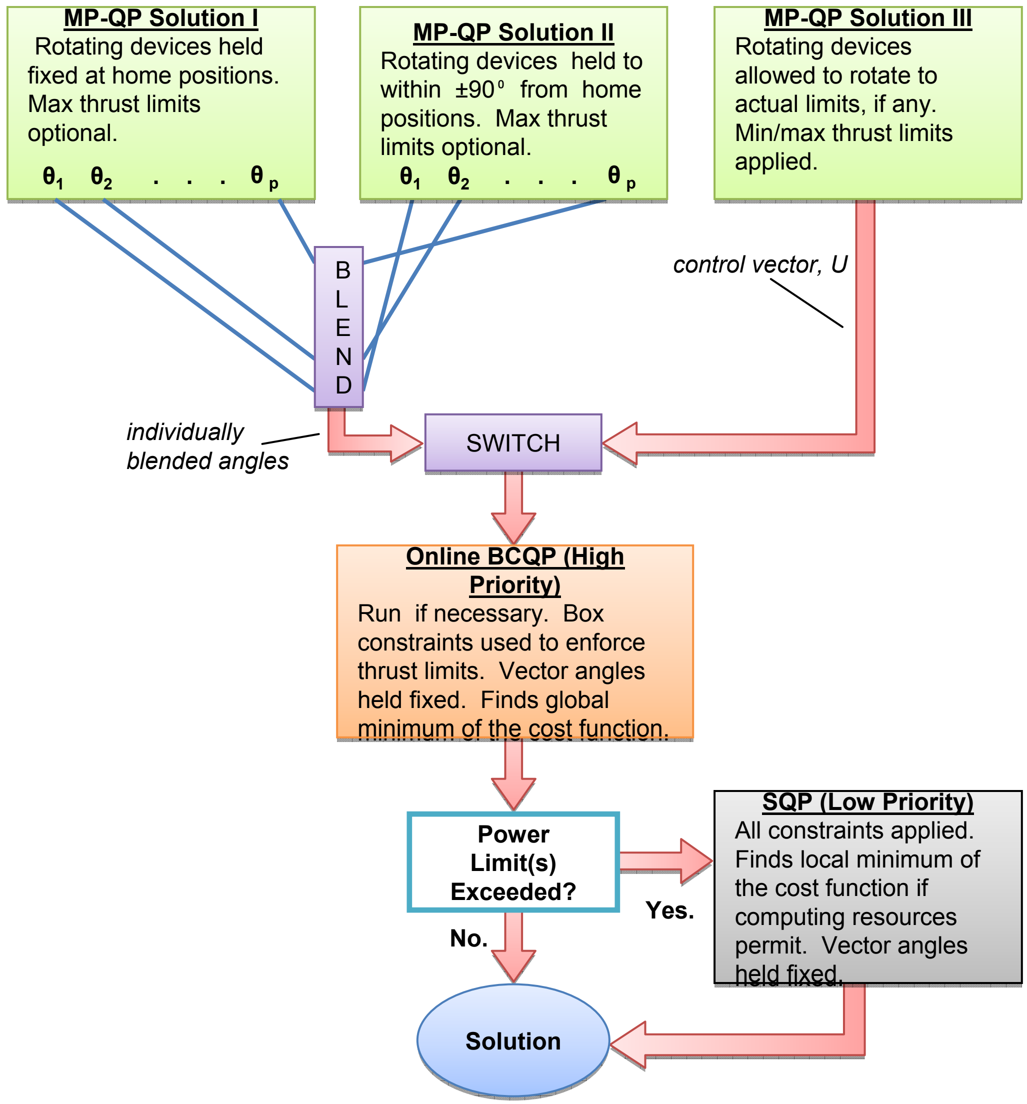


PROPOSED SOLUTION

GENERALIZED ALLOCATION ALGORITHM

- rotating devices are handled by blending 3 MP-QP solutions
- Solution I – fixed axis
- Solution II – rotation is semi-constrained
- Solution III – rotation is not artificially constrained
- angular blending is individually applied to each device
- algorithm is a hybrid of offline and online approaches

GENERALIZED ALLOCATION ALGORITHM

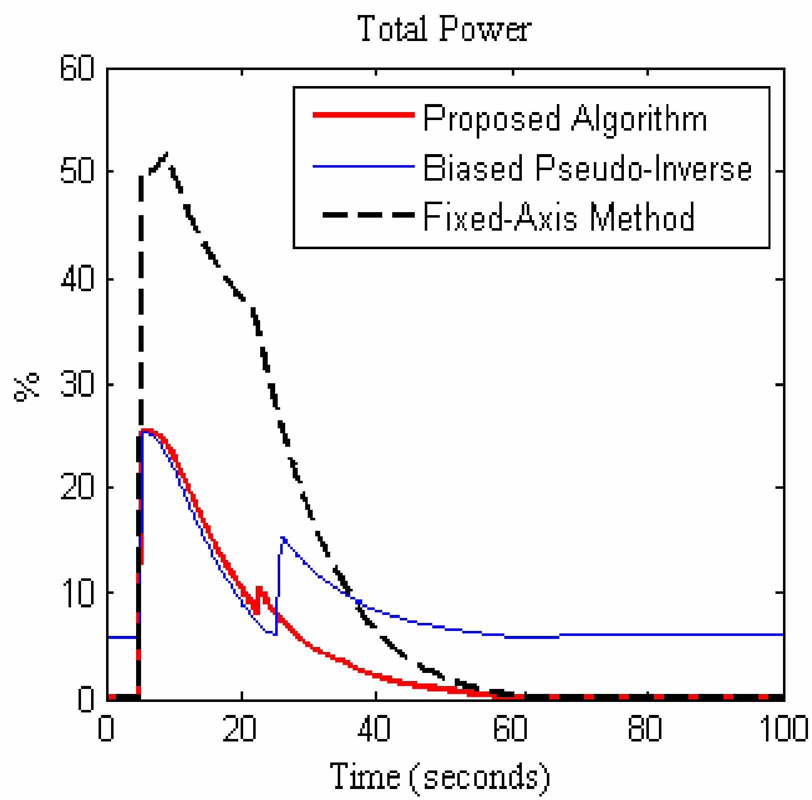


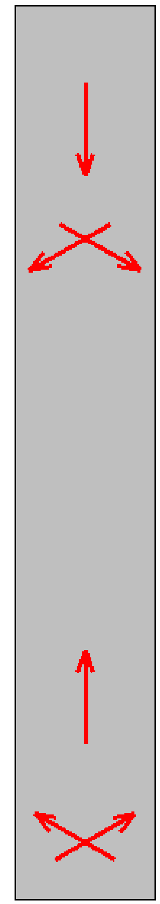
IMPROVEMENTS OVER MP-QP

- hunting/fluttering of rotating devices is operator adjustable
- angular rate limits can be directly applied
- azi home positions are configurable online
- spoil zones, non-zero minimum thrust, etc. can be handled (sub-optimally)
- provision is made for optimal power limiting

MATLAB SIMULATION

- Drillship with 6 azimuthing thrusters
- Random periodic impulse applied
- No power or rate limiting





CONCLUSIONS

- An optimal allocation algorithm has been proposed
- Although it is an online implementation, it evaluates relatively quickly
- The algorithm is flexible enough to be applied to any vessel
- A number of special cases can be handled (power limiting, spoil zones, etc.)