Developing MOOS-IvP Interfaces to OPL/CPLEX Optimization Software and a Novel Mission Visualizer

MOOS-DAWG 2015

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Outline

- NSWC PCD Overview
- Motivation
- OPL/CPLEX Overview
- pMOI –Mathematical Optimization Interface for MOOS-IvP
- NSWC PCD's Mine Warfare Visualizer
- Mine Warfare Visualizer API and use with MOOS-IvP
- Summary

NAVSEA Warfare Centers

- Provide research and development (R&D), test and evaluation (T&E) for the future Navy and in-service engineering and logistics support to the current Navy Fleet
- Business-based enterprise operating under the Navy Working Capital Fund
- Critical concentration of scientists, engineers and technicians (~18,000) with over 600 PhDs
- Unimpeded access to unique military facilities and technical capabilities

Warfare Centers (WFCs) exist to:

- Understand the technical dimensions of military problems
- Liaison with industry and academia to define the best solutions
- Provide quality assurance for Navy Programs
- Provide lifecycle support for Navy ship and submarine systems

Products and Services Output

- In-Service solutions for Today's Fleet
- Technical Authority Advice and Decisions
- Interoperable Warfare Systems
- Innovation to provide technology solutions and facilitate technology transition to Tomorrow's Fleet

Mission & Vision

VISION: Technical Center of Excellence for Littoral Warfare and Coastal Defense

NSWC PCD MISSION:

Conduct Research, Development, Test, Evaluation, and Life Cycle Sustainment work within our assigned mission areas that enable the Navy to remain a Global Force for Good:

- Mine Warfare
- Naval Special Warfare Systems
- Diving & Life Support Systems
- Amphibious/Expeditionary Maneuver Warfare Systems
- other missions that occur primarily in coastal (littoral) regions

END STATE: Rapidly deliver Littoral Warfare and Coastal Defense capability to the warfighter through technical rigor, accountable leadership, and stakeholder partnerships.

Value to the Warfighter

SCIENCE & TECHNOLOGY

- Advanced Sensors
- Signal Processing & Information Fusion
- Automation & Dynamics
- Cognitive Architectures
- Target Scattering
- Search Theory Modernization

RESEARCH & DEVELOPMENT

- Air Cushion Vehicle Systems (LCAC100)
- USMC Route Reconnaissance & Clearance
- Expeditionary C2
- Mission Package Application Software
- MH-60S/AMCM Integration
- Mission Capable Unmanned System

TEST & EVALUATION

- LCS Mission Package IO&TE Certification and IOT&E
- Naval Mine Warfare Simulation (NMWS)
- MH-60S/AMNS Live Fire
- Foreign Weapon Exploitation
- Expeditionary Energy Evaluation
- Human Systems Integration

PRODUCT DELIVERY

- MK18 EOD UUV
- LCAC SLEP
- Expeditionary C2 (DJC2,USMC, MLP, NETC2)
- SQQ-32 (V)4Sonar Upgrades
- AAG/IAAG Acoustic Sweeps
- ASQ-232 (SeaFox RDC)

FLEET SUPPORT

- SEAL Delivery Vehicles(SDV) Restricted Overhauls
- USMC Mine Roller Family of Systems
- Chem/Bio Individual Protection
- Damage Control Personnel Protection
- USMC Raids & Recon
- SEAVIEW
- MCM Tactics & Doctrine
- MIW Sustainment (MCM 1, MH-53E, Mines)

NAVSEA WARFARE CENTERS PANAMA CITY

- Non-Mag Area & Fanselau Coil
- Littoral Warfare Integration Facility
- Joint Gulf Test Range
- Sea Fighter (FSF-1)
- Fleet Liaison & Aviation Det
- Prototype Fabrication Facility

National Unmanned Systems Shared Resource Center (NUSSRC)

Objective:

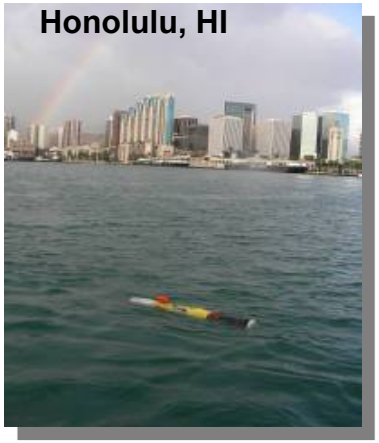
Provide advanced ONR technologies to Fleet units, S & T and acquisition programs. Provides reduction in Total Ownership Costs by leveraging previous investments in Unmanned Systems.

REMUS 100

Clear Horizon (CHINHAE, ROK)
Multi-National MCM Exercise

San Diego Harbor MHD Exercise
ONR, NOMWC and Orca Maritime

RIMPAC/MINEX
Honolulu, HI



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Motivation

- As maritime autonomy is introduced to perform increasingly complex missions, there is a prevailing need to
  - Autonomously determine complex event sequences, waypoint planning, and task schedules.
  - Visualizing those vehicle actions before a mission in great detail.

- Currently, off-the-shelf MOOS-IvP has basic functionality that help with these needs.
  - IvP Helm
  - pMarineViewer

- However, there are some advanced capabilities that could further meet these needs.

Motivation

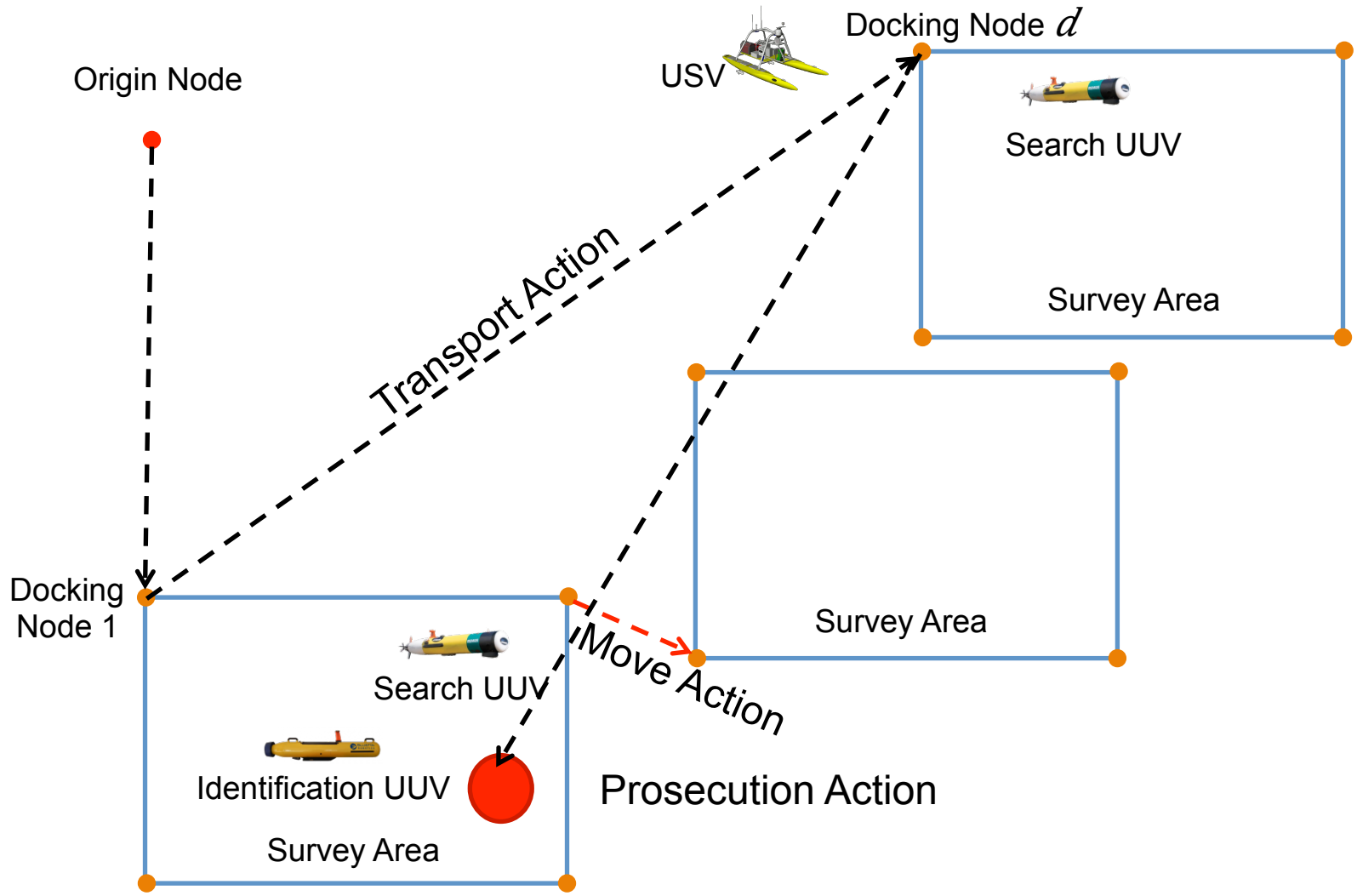
Extending Capabilities

- On the planning side
  - Non-IvP optimization methods.
  - Constraint-compliant programming.
  - Complicated task sequencing.

- On the mission visualization side
  - 3D visualization.
  - Vehicle point-of-view introspection.
  - Making ***really cool*** simulation demonstrations.

- We believe the following tools & MOOS-IvP interfaces will help with these capabilities.

Ex: Survey & Transport Scheduling



Ex: Survey & Transport Scheduling

Minimize $\max_a \bar{\mathbf{T}}^{end}_{a,P}$

Subject to

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{mn,p} = \sum_{p' \le p, d \in D} \bar{\mathbf{I}}^{dock}_{mn,p',d} - \bar{\mathbf{I}}^{deploy,}_{mn,p',d}$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{mn,p} \ge 0$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{mn,p} \le 1$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{m,p} = \sum_{n \in \mathcal{N}} \bar{\mathbf{D}}_{mn,p}$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{m,p} \ge 0$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{m,p} \le 1$$

$$\forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \sum_{m \in \mathcal{M}} \bar{\mathbf{D}}_{mn,p} \le D_{max}$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P}$$

$$\bar{\mathbf{F}}_{m,p} = \sum_{p' \le p} \Bigg[\bar{\mathbf{F}}^{charge}_{m,p'} - \sum_{s \in \mathcal{S}} f^{survey}_{m,p',s} \bar{\mathbf{I}}^{survey}_{m,p',s} - \sum_{d \in \mathcal{D}} \left(f^{dock}_{m,p',d} \bar{\mathbf{I}}^{dock}_{m,p',d} + f^{deploy}_{m,p',d} \bar{\mathbf{I}}^{deploy}_{m,p',d} \right) - \sum_{v \in \mathcal{V}} f^{move}_{m,p',v} \bar{\mathbf{I}}^{move}_{m,p',v} \Bigg]$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{D}}_{m,p} = 1 \Rightarrow \bar{\mathbf{F}}^{charge}_{m,p} = c^{charge}_a \left(\bar{\mathbf{T}}^{end}_{m,p} - \bar{\mathbf{T}}^{start}_{m,p} \right)$$

$$\bar{\mathbf{D}}_{m,p} = 0 \Rightarrow \bar{\mathbf{F}}^{charge}_{m,p} = 0$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{F}}_{m,p} \le F_{max}$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad 0 \le \bar{\mathbf{F}}_{m,p}$$

$$\forall a \in \mathcal{A}, \forall p \in \mathcal{P} \qquad \sum_{k \in \mathcal{K}} \sum_{\mathcal{L} \in \mathcal{L}_k} \bar{\mathbf{I}}^k_{a,p,\mathcal{L}} \le 1$$

$$\forall a \notin \mathcal{A}_k, \forall p \in \mathcal{P}, \forall \mathcal{L} \in \mathcal{L}_k \qquad \bar{\mathbf{I}}^k_{a,p,\mathcal{L}} = 0$$

$$\forall a \in \mathcal{A} \qquad \bar{\mathbf{T}}^{start}_{a,p=0} = 0$$

$$\forall a \in A, \forall p \in \mathcal{P}/p = 0 \qquad \bar{\mathbf{T}}^{start}_{a,p+1} \ge \bar{\mathbf{T}}^{end}_{a,p}$$

$$\forall a \in \mathcal{A}, \forall p \in \mathcal{P} \qquad \bar{\mathbf{T}}^{end}_{a,p} = \bar{\mathbf{T}}^{start}_{a,p} + \sum_{k \in \mathcal{K}} \sum_{\mathcal{L} \in \mathcal{L}_k} c^k_{a,\mathcal{L}} \bar{\mathbf{I}}^k_{a,p,\mathcal{L}}$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{dock}_{mn,p,d} = 1 \Rightarrow \bar{\mathbf{T}}^{start}_{m,p} = \bar{\mathbf{T}}^{start}_{n,p}$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P} \qquad \sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{deploy}_{mn,p,d} = 1 \Rightarrow \bar{\mathbf{T}}^{start}_{m,p} = \bar{\mathbf{T}}^{start}_{n,p}$$

$$\forall a \in \mathcal{A}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D} \qquad \sum_{k \in \mathcal{K}} \left[\sum_{\mathcal{L} \in \mathcal{L}_k} \bar{\mathbf{I}}^k_{a,p,\mathcal{L}} \right] + \sum_{\substack{d' \in \mathcal{D} \\ \text{s.t. } d' \ne d}} \bar{\mathbf{I}}^{wait}_{a,p,d'} = 1 \Rightarrow \bar{\mathbf{I}}^{wai}_{a,p}$$

Subject to (cont.)

$$\forall a \in \mathcal{A}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}$$

$$\sum_{k \in \mathcal{K}} \left[\sum_{\substack{\mathcal{L} \in \mathcal{L}_k \\ \text{s.t. } d \notin \mathcal{L}}} \bar{\mathbf{I}}^k_{a,p-1,\mathcal{L}} \right] + \sum_{\substack{d' \in \mathcal{D} \\ \text{s.t. } d' \ne d}} \bar{\mathbf{I}}^{wait}_{a,p-1,d'} = 1 \Rightarrow \bar{\mathbf{I}}^{wait}_{a,p,d} = 0$$

$$\forall a \in \mathcal{A}, \forall p \in \mathcal{P} \qquad \sum_{k \in \mathcal{K}} \sum_{\mathcal{L} \in \mathcal{L}_k} \bar{\mathbf{I}}^k_{a,p,\mathcal{L}} = 0 \Rightarrow \sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{wait}_{a,p,d} = 1$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall d_0 \in D$$

$$\sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{move}_{m,p,(d_0,d)} = 1 \Rightarrow \sum_{d' \in \mathcal{D}} \bar{\mathbf{I}}^{move}_{m,p-1,(d',d_0)} + \sum_{n \in N} \bar{\mathbf{I}}^{deploy}_{mn,p-1,d_0} + \sum_{s \in \mathcal{S} s.t. d_0 \in \mathcal{D}_s} \bar{\mathbf{I}}^{survey}_{m,p-1,s} + \bar{\mathbf{I}}^{wait}_{m,p-1,d} = 1$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \sum_{v \in \mathcal{V}} \bar{\mathbf{I}}^{move}_{m,p,v} = 1 \Rightarrow \bar{\mathbf{D}}_{m,p} = 0$$

$$\forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall v \in \mathcal{V} \qquad \sum_{m \in \mathcal{M}} \bar{\mathbf{I}}^{transport}_{mn,p,v} \ge 1 \Rightarrow \bar{\mathbf{I}}^{transport}_{n,p,v} = 1$$

$$\forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall v \in \mathcal{V} \qquad \sum_{m \in \mathcal{M}} \bar{\mathbf{I}}^{transport}_{mn,p,v} = 0 \Rightarrow \bar{\mathbf{I}}^{transport}_{n,p,v} = 0$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}$$

$$\bar{\mathbf{I}}^{dock}_{mn,p,d} = 1 \Rightarrow \sum_{d_{0_1} \in D} \bar{\mathbf{I}}^{move}_{m,p-1,(d_{0_1},d)} + \bar{\mathbf{I}}^{wait}_{m,p-1,d} + \sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{survey}_{m,p-1,ds} = 1$$

$$\bar{\mathbf{I}}^{dock}_{mn,p,d} = 1 \Rightarrow \sum_{d_{0_1} \in D} \left[\bar{\mathbf{I}}^{move}_{n,p-1,(d_{0_1},d)} + \sum_{\substack{m' \in \mathcal{M} \\ \text{s.t. } m' \ne m}} \bar{\mathbf{I}}^{transport}_{mn,p-1,v} \right] + \bar{\mathbf{I}}^{wait}_{n,p-1,d}$$

$$+ \sum_{\substack{m' \in \mathcal{M} \\ \text{s.t. } m' \ne m}} \left[\bar{\mathbf{I}}^{dock}_{m'n,p-1,d} + \bar{\mathbf{I}}^{deploy}_{m'n,p-1,d} \right] \ge 1$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}$$

$$\bar{\mathbf{I}}^{deploy}_{mn,p,d} = 1 \Rightarrow \sum_{d_{0_1} \in D} \bar{\mathbf{I}}^{transport}_{mn,p-1,(d_{0_1},d)} + \bar{\mathbf{I}}^{wait}_{m,p-1,d} = 1$$

$$\bar{\mathbf{I}}^{deploy}_{mn,p,d} = 1 \Rightarrow \sum_{d_{0_1} \in D} \bar{\mathbf{I}}^{transport}_{mn,p-1,(d_{0_1},d)} + \bar{\mathbf{I}}^{wait}_{n,p-1,d} + \sum_{\substack{m' \in \mathcal{M} \\ \text{s.t. } m' \ne m}} \left[\bar{\mathbf{I}}^{dock}_{m'n,p-1,d} + \bar{\mathbf{I}}^{deploy}_{m'n,p-1,d} \right] \ge 1$$

$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall v \in \mathcal{V} \qquad \bar{\mathbf{I}}^{transport}_{mn,p,v} = 1 \Rightarrow \bar{\mathbf{D}}_{mn,p} = 1$$

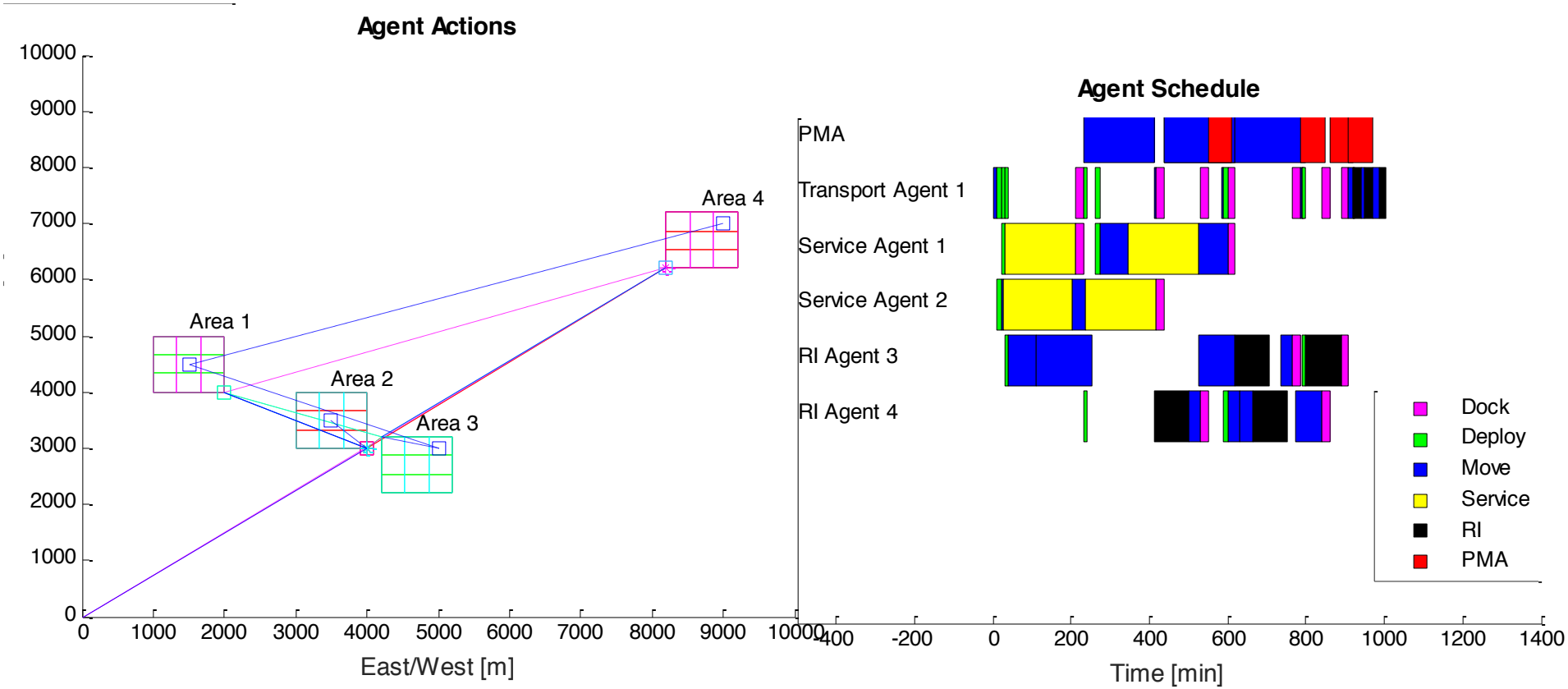
$$\forall m \in \mathcal{M}, \forall n \in \mathcal{N}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}, \forall s \in \mathcal{S} \qquad \bar{\mathbf{I}}^{survey}_{m,p,ds} = 1 \Rightarrow \sum_{n \in \mathcal{N}} \bar{\mathbf{I}}^{deploy}_{mn,p-1,d} + \sum_{d' \in D} \bar{\mathbf{I}}^{move}_{m,p-1,(d',d)} = 1$$

$$\forall m \in \mathcal{M}, \forall p \in \mathcal{P} \qquad \sum_{s \in \mathcal{S}} \bar{\mathbf{I}}^{survey}_{m,p,s} = 1 \Rightarrow \bar{\mathbf{D}}_{m,p} = 0$$

$$\forall s \in \mathcal{S} \qquad \sum_{p \in \mathcal{P}} \sum_{m \in \mathcal{M}} \sum_{d \in \mathcal{D}} \bar{\mathbf{I}}^{survey}_{m,p,ds} = 1$$

M.J. Bays & T. A. Wettergren, "A Solution to the Service Agent Transport Problem," *IEEE IROS*, Accepted.

Ex: Survey & Transport Scheduling



M.J. Bays, R.D. Tatum, L. Cofer, & J. Perkins, "Automated Scheduling and Mission Visualization for Mine Countermeasure Operations", *IEEE OCEANS*, Accepted.

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OPL/CPLEX Overview

What is OPL and CPLEX?

- OPL: Optimization Programming Language
  - Published by IBM as part of their Optimization Studio.
  - Allows for high-level, fast prototyping of optimization models
  - Models are created in *.mod files, external data is populated in *.dat files
- CPLEX Optimization Capabilities:
  - Runs optimization models written in OPL, or in canonical forms
    - Linear Programming
    - Integer-Linear Programming
    - Quadratic programming
    - Constraint Programming
  - API's including Java, C++, VB, C#.

OPL/CPLEX Overview

Mixed Integer Linear Programming Overview

- Linear programming: mathematical optimization problem having a linear objective function and linear constraints

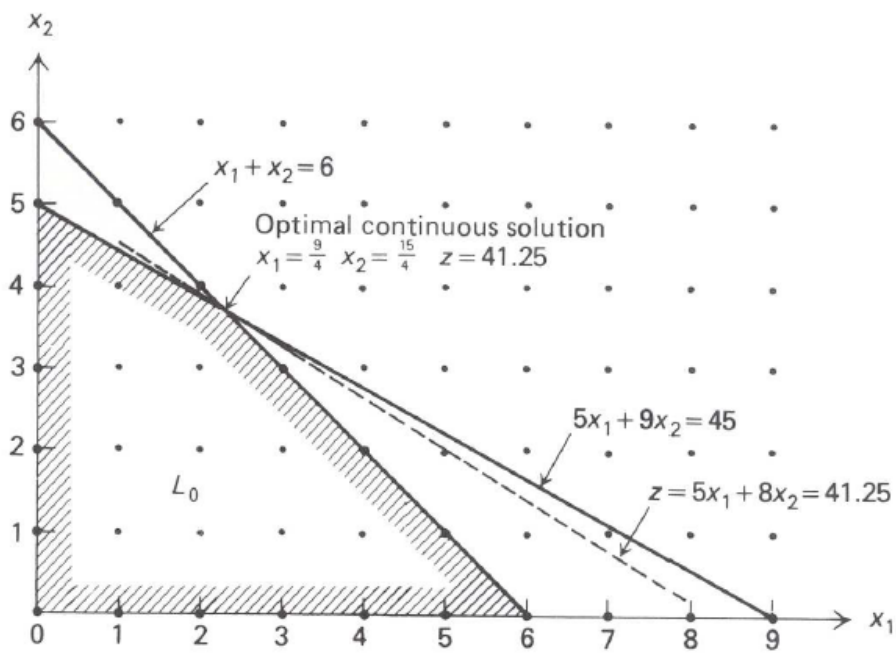


Figure 9.8 An integer programming example.

- Canonical form:
  Maximize $c^T x$
  Subject to $Ax \leq b$
  $x \geq 0$
  $x \in \mathbb{Z}$
- Often used for scheduling problems and chemical processing.
- Becoming increasingly prevalent in robotics research.

Figure credit: web.mit.edu/15.053/www/AMP-Chapter-09.pdf

OPL/CPLEX Overview

Decision Variables, Model Elements, and Accessors

General OPL decision variable/model element construction:

$$\left.\begin{array}{l} type\ N1 = \ldots; \\ type\ N2 = \ldots; \\ \vdots \\ type\ N(n) = \ldots; \end{array}\right\}$$

Constants populated from *.dat file

$$\left.\begin{array}{l} type\ range\ r1 = s1..N1; \\ type\ range\ r2 = s2\ ..\ N2; \\ \vdots \\ type\ range\ r(n) = s(n)..N(n); \end{array}\right\}$$

Accessors

$$\left.\begin{array}{l} dVar\ type\ var1[r1][r2]\ldots[r(n)]; \\ dVar\ type\ var2[r1][r2]\ldots[r(n)]; \\ \vdots \\ dVar\ type\ var(n)[r1][r2]\ldots[r(n)]; \end{array}\right\}$$

Decision Variables

Minefield Optimization

OPL Overview: Example Model Snippet (*.mod)

```
int nNodes      = ...;
int M = ...;
int N = ...;

float originPoint[1..2] =...;
int c_service = ...;
float f_move = ...;

tuple area {int nodeGraph[Nodes];};
{area} Areas;

dvar boolean Idock[Atransport][Aservice][Phases][Nodes];
dvar boolean Ideploy[Atransport][Aservice][Phases][Nodes];

minimize (max(a in Atot)Tend[a][P]);
subject to {
  //TransportGen is generalized sum of m for Itransport.
  forall(n in Atransport, p in Phases, e in Edges)
    sum(m in Aservice) Itransport[n][m][p][e] >= 1 => ItransportGen[n][p][e] == 1;

  forall(n in Atransport, p in Phases, e in Edges)
    sum(m in Aservice) Itransport[n][m][p][e] ==0 => ItransportGen[n][p][e] == 0;

…}
```

OPL/CPLEX Overview

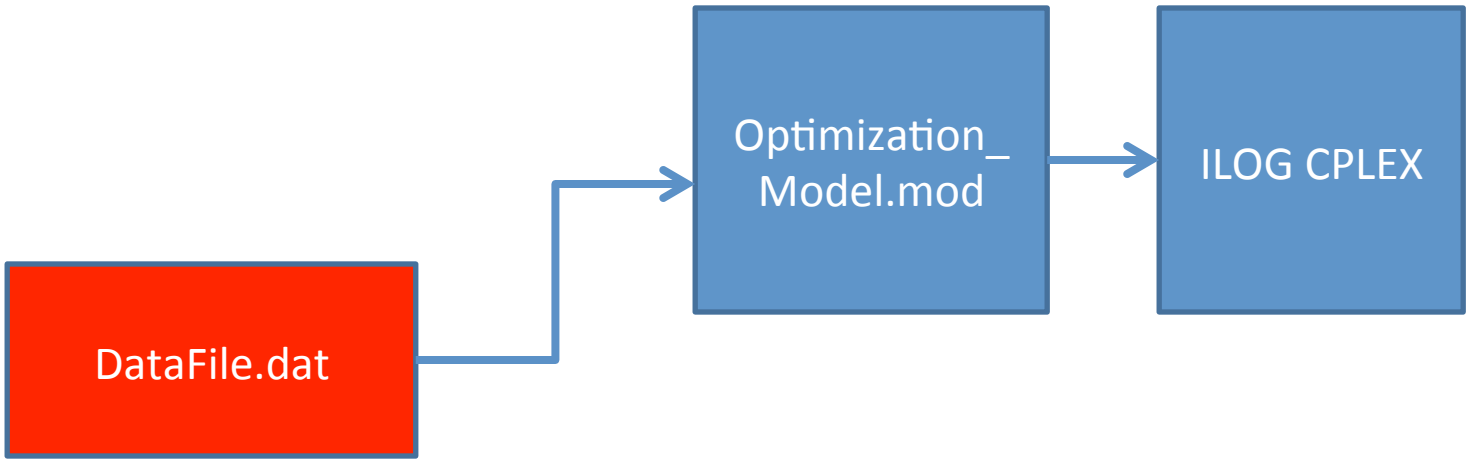
Data Files (*.dat)

```
 f_dock = 1;
f_deploy = 1;
f_service = 20;
f_move = .001;
Finit = 100;
N=2;

TravelCost={49.6904
55.5556
58.6684
114.2231
49.6904
24.8452
26.0104
73.0973
55.5556
24.8452
};
```

OPL/CPLEX Overview

Information Flow



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MOOS-OPL Interface

Motivation

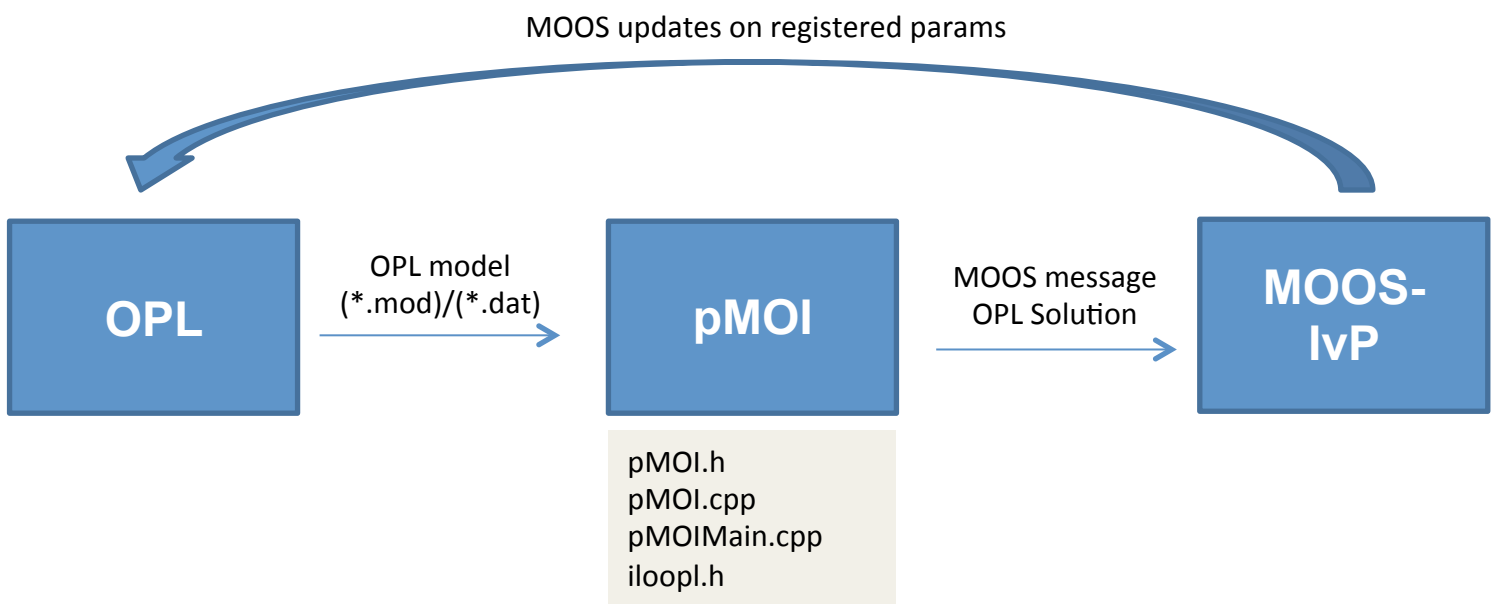
- We desire to use the mathematical optimization software to perform planning/scheduling tasks for a pre-written optimization problem (written in OPL), but populated with data collected from the vehicle.

- Data variables and their respective types as parameters in .moos files.

- Start optimization once all required data is populated and a certain variable is posted to the MOOSDB.

MOOS-OPL Interface

High Level Overview



- By inserting pMOI between OPL and MOOS-IvP autonomy software, you give the power of optimization to the unmanned vehicle

MOOS-OPL Interface

Decision Variables, Model Elements, and Accessors Cont'd

Model file (*.mod) equivalent:

range x_coord = ...;
range y_coord = ...;

tuple xy_coords = {x,y};
range speed = ...;

dVar int coords[x_coord][y_coord];
dVar float+ times[xy_coords][speed];
dVar bool sensors[xy_coords];

Translation

Mission file (*.moos) equivalent:

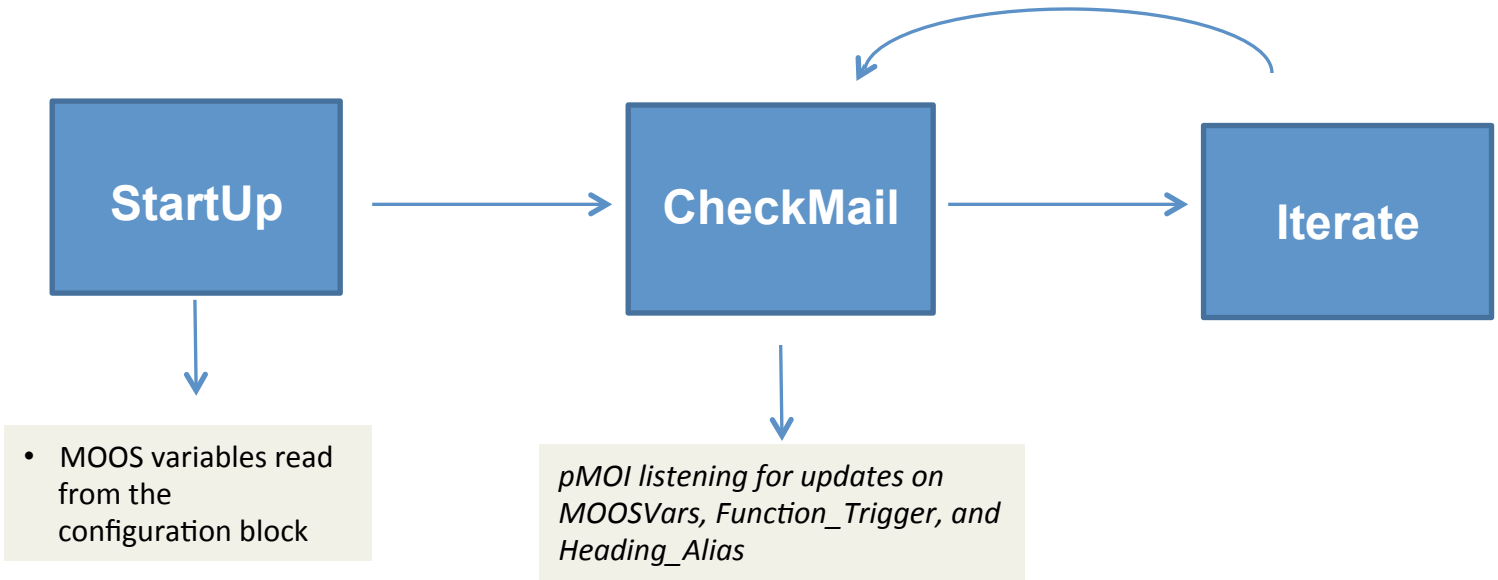
ProcessConfig = pMOI
{
⋮
MOI_OPL_Decision_Var_Types = int, float+, bool
MOI_OPL_Decision_Var_Names = coords, times, sensors
MOI_OPL_Decision_Var_Accessor_Types = int range, int range; tuple set, int range; tuple set
MOI_OPL_Decision_Var_Accessor_Names = NAV_X, NAV_Y; xy_coords, speed; xy_coords
⋮
}

MOOS-OPL Interface

How pMOI Fits Into MOOS-IvP CMOOSApp Über-loop

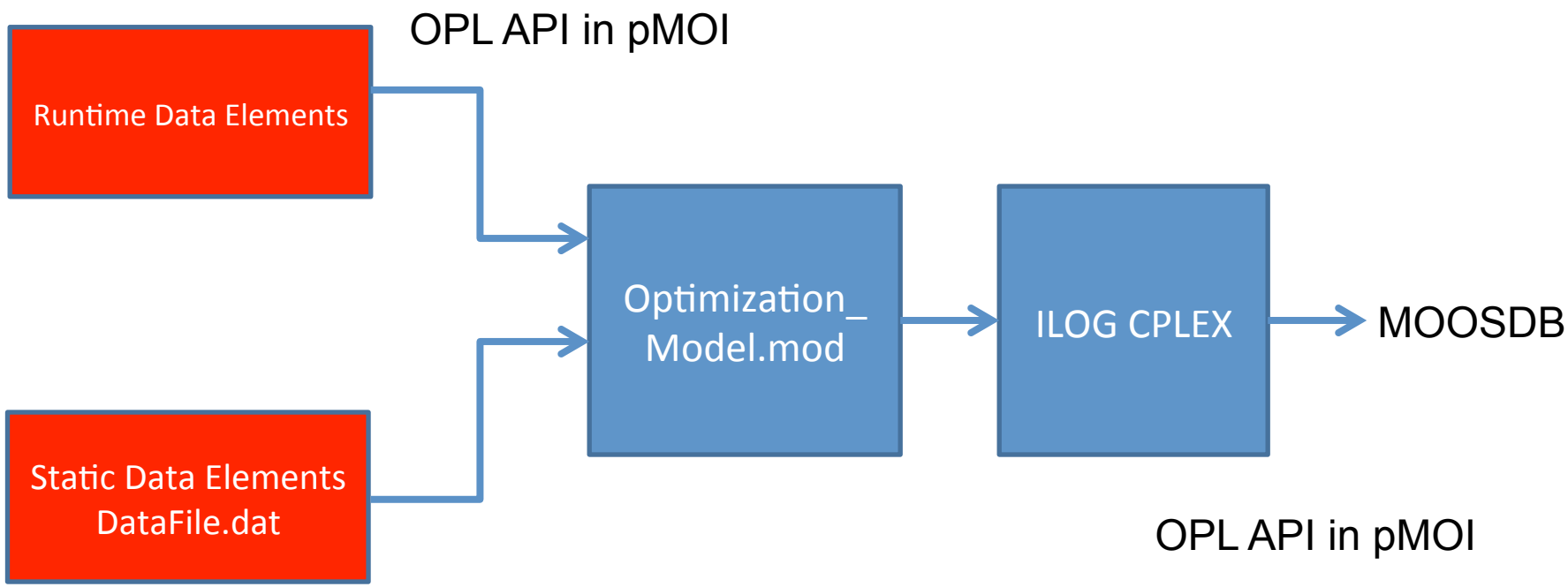
General Function Call Sequence for CMOOSApps:

CMOOSApp::Run()



MOOS-OPL Interface

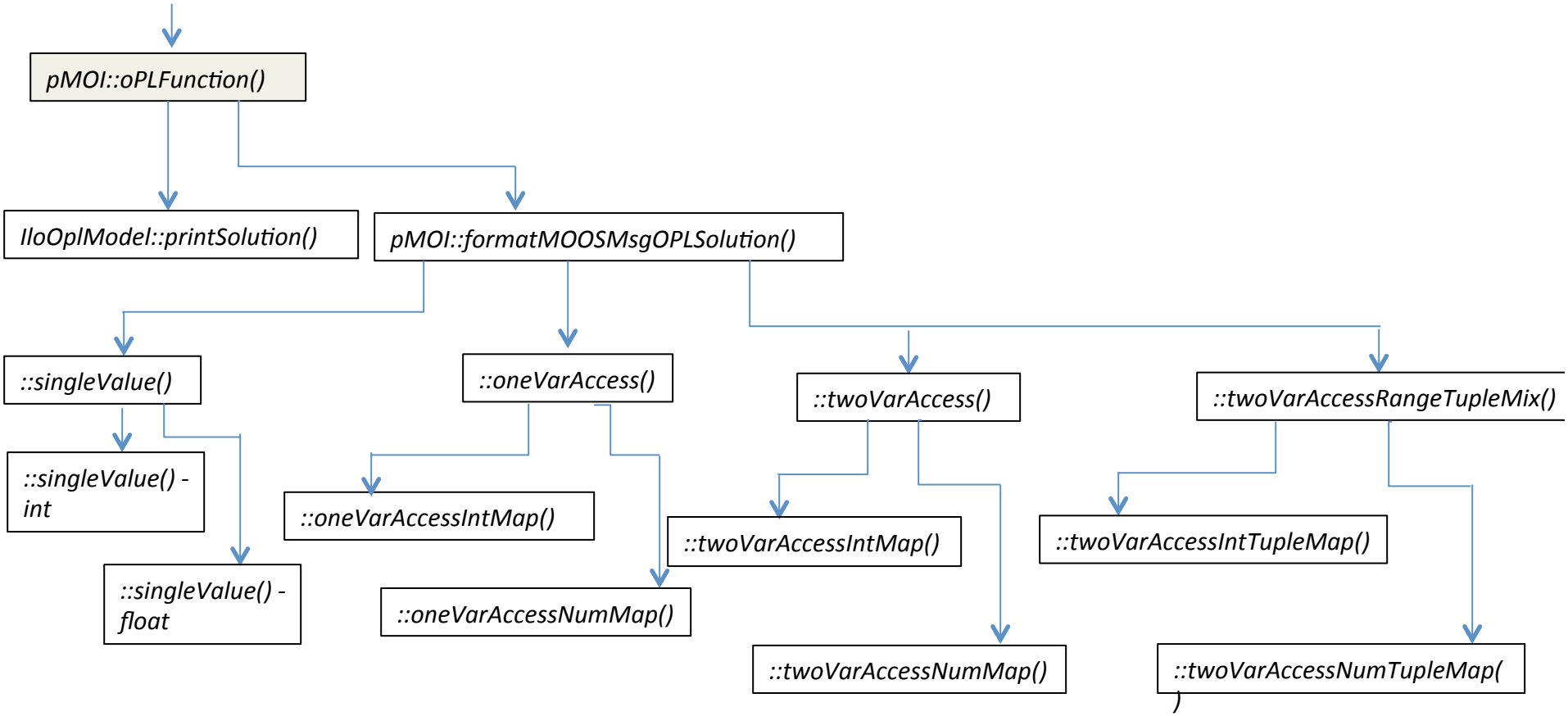
Information Flow



MOOS OPL Interface

How pMOI Fits Into MOOS-IvP CMOOSApp Uber-Loop Cont'd.

pMOI Functional Sequence:



It's off to the MOOSDB!!!

MOOS-CPLEX Autonomy Video

Sensor Placement

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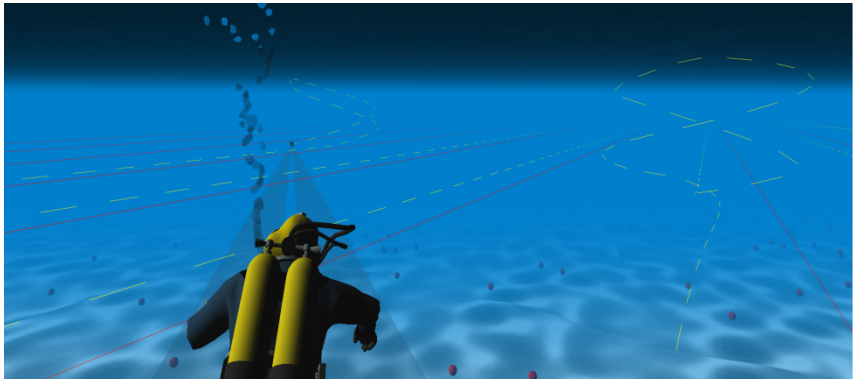
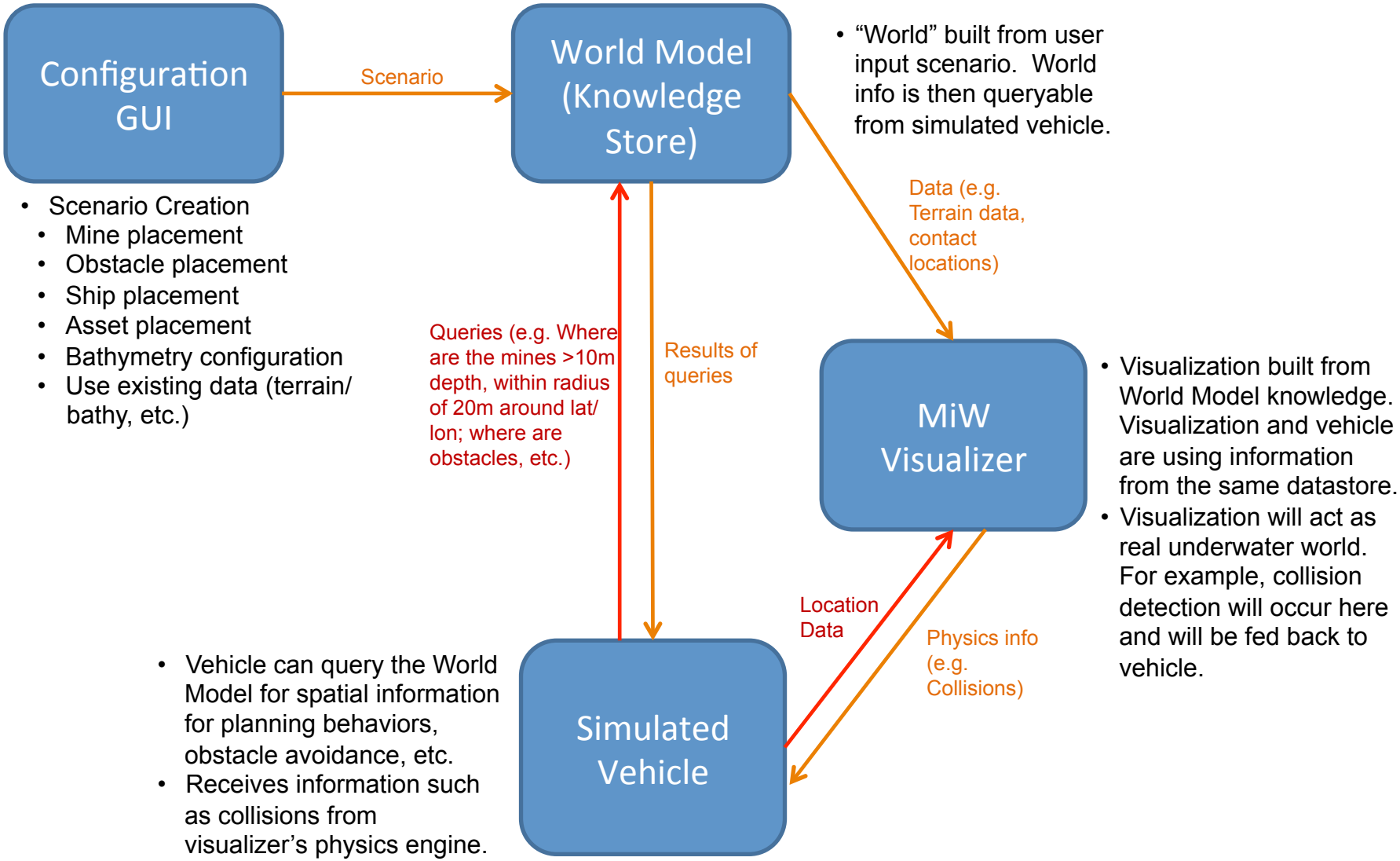
PCD's MIW Visualizer

Overview

- 2 Parts: Visualizer and Web management interface
- 3 Dimensional, real-time or log file playback display of multiple vehicles
    - Currently supports position/orientation, planned paths, contacts
- Can add any vehicle/object if you have a 3D model
- Built on Open Scene Graph and the Vizard abstraction layer.
- Can easily configure environment. Contacts, area, bathymetry/obstacles (EoY FY15)
- Land, surface and underwater
- Works with normal monitor or VR Goggles (including Oculus Rift)
- Created for developers to improve systems, but useful for project reviews, VIP demonstrations, etc.
- Easily distributable

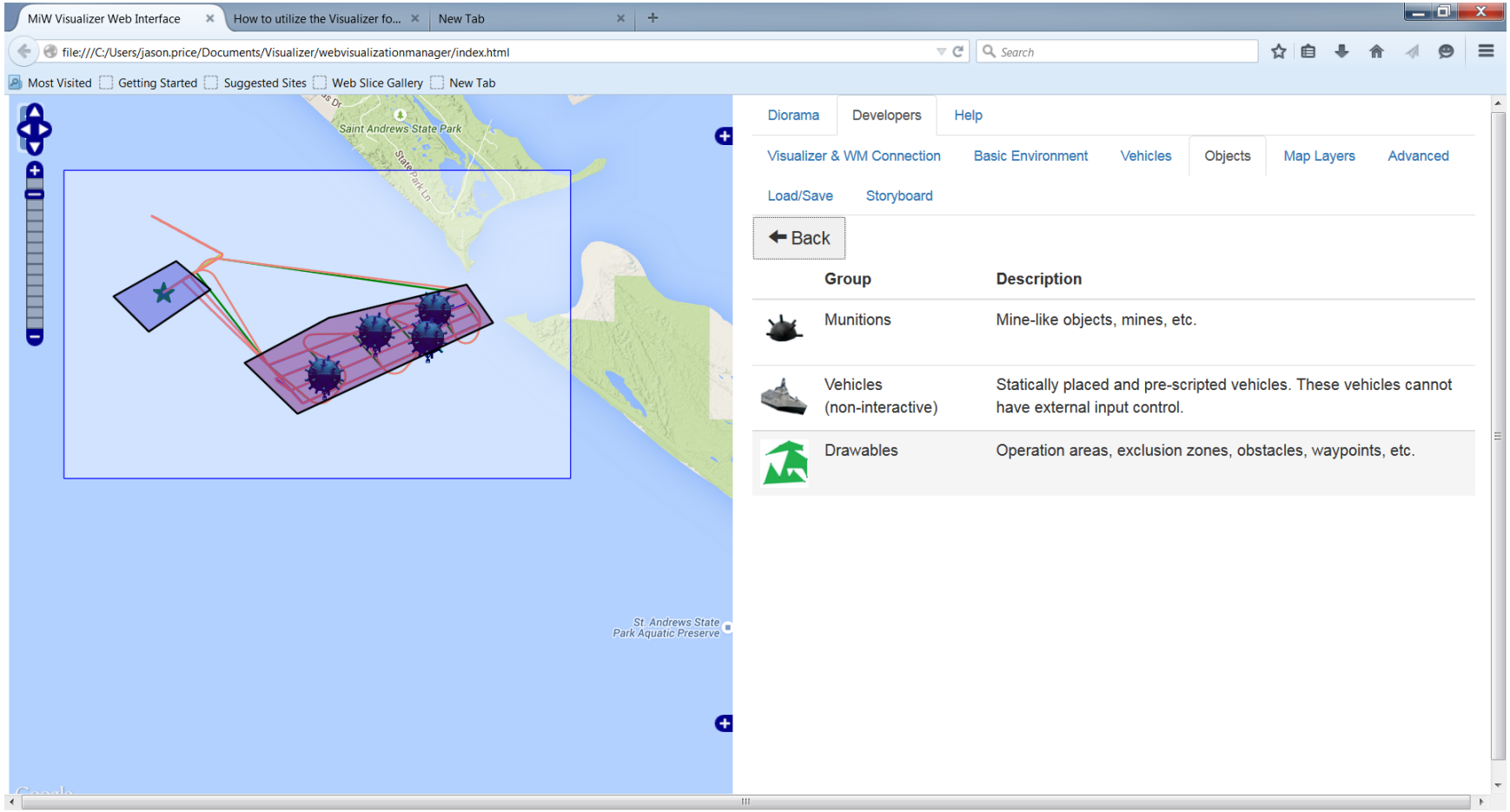


PCD's MIW Visualizer



PCD's MIW Visualizer

Web management Interface

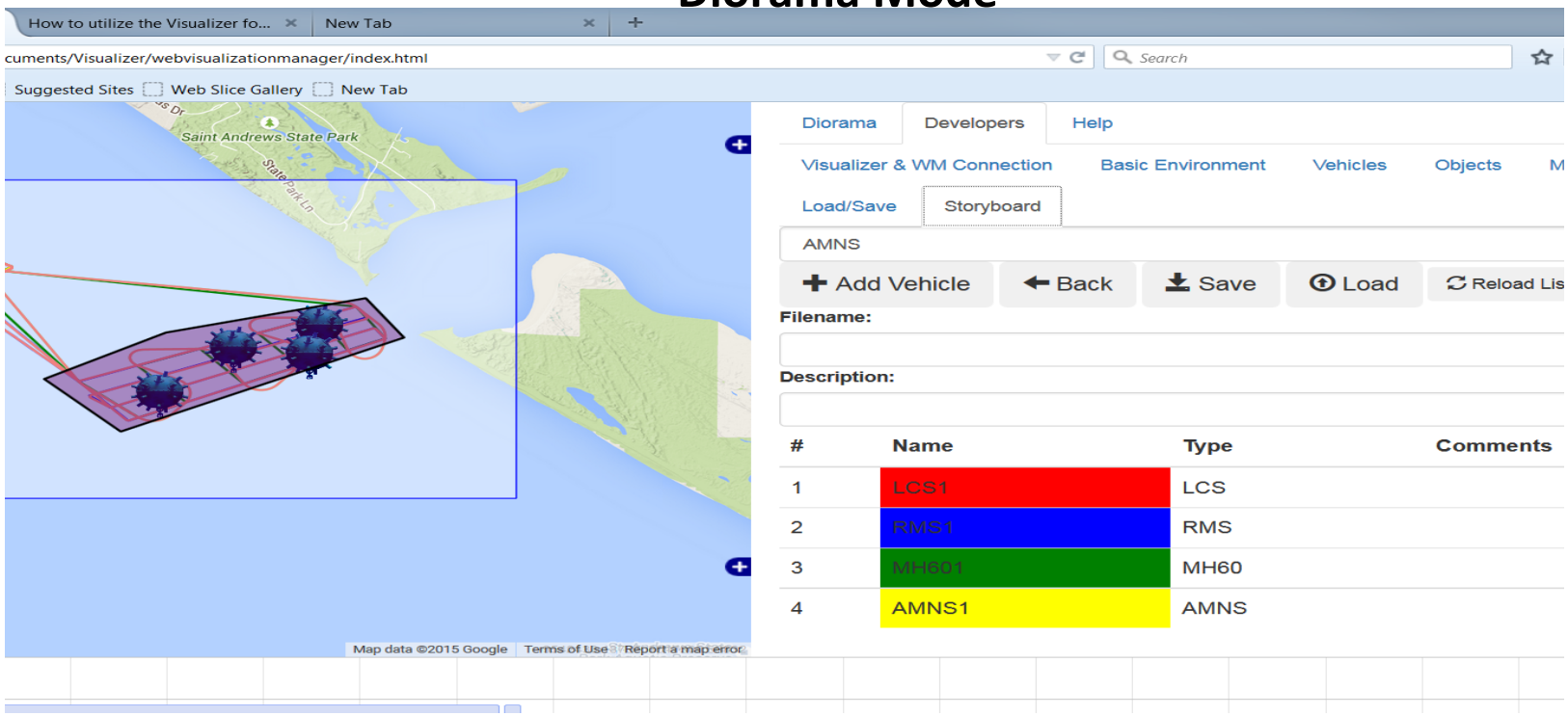


PCD's MIW Visualizer

Visualizer

PCD's MIW Visualizer

Diorama Mode



- Create full vehicle missions and watch them play out in the visualizer
- Useful for displaying innovative systems that are not yet developed to sponsors, VIPs, etc.
- Can plan each waypoint and event for vehicles, including vehicle interaction (e.g. launch/recovery)
- Builds on top of MIW Visualizer architecture.
- Ongoing research: Evaluate user-made missions according to system metrics

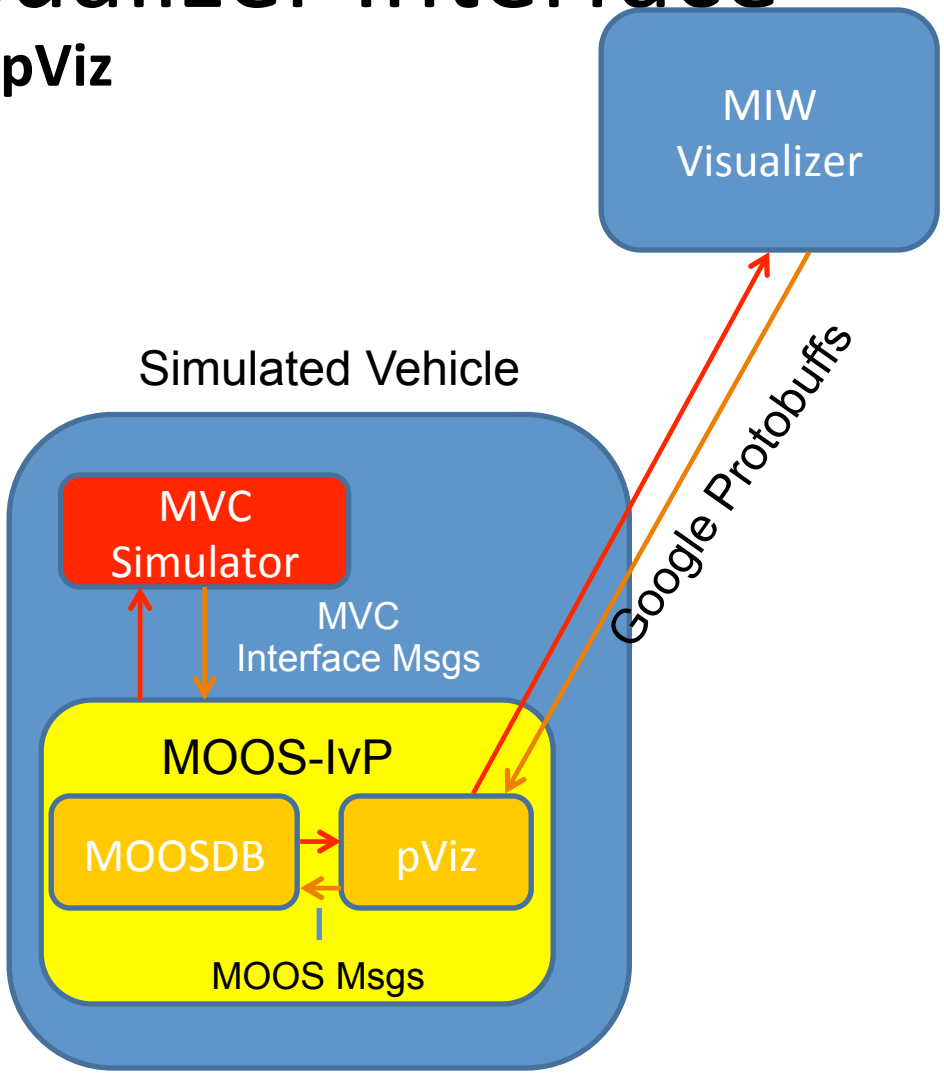
Outline

- NSWC PCD Overview
- Motivation
- OPL/CPLEX Overview
- pMOI –Mathematical Optimization Interface for MOOS-IvP
- NSWC PCD's Mine Warfare Visualizer
- **Mine Warfare Visualizer API and use with MOOS-IvP**
- Summary

MOOS-IvP/Visualizer Interface

pViz

- Consists of MOOS Module that acts similar to a Main Vehicle Computer (MVC) interface such as iREMUS or iFrontSeat.
- Takes NAV_X and NAV_Y MOOS Messages, and translates them to Google Protocol Buffer messages.
- Additionally, uses timestamp information to interpolate vizualizer vehicle motion in-between messages.



PCD's MIW Visualizer

Visualizer

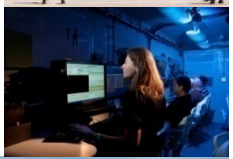
Summary

- Presented interfaces to IBM's ILOG CPLEX and a novel visualizer to MOOS-IvP.
- ILOG CPLEX interface allows mathematical optimization techniques to be used in autonomous UxVs running MOOS-IvP.
- MIW Visualizer allows 3D modeling, simulation, and mission playback of UxV missions with open interfaces, including MOOS-IvP.

Shameless Plug

- We're looking for potential collaborators…

- **…and potential NSWC PCD researchers!**
  - U.S. Citizenship required
  - Multiple positions
    - Autonomy, signal processing, basic research…



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