Distributed, Adaptive Control of Advanced Life Support Systems

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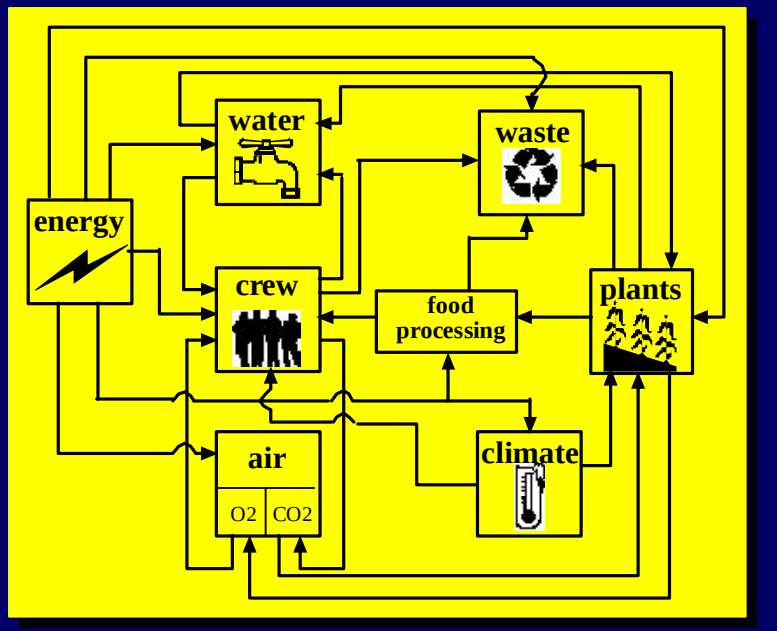
Advanced Life Support Systems

- Regenerative
  - produce own food
  - recycle water and air
- Low margins, volume, mass, energy and labor
- Limited resupply
- Highly interconnected
- Require optimization and tight control



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Control Issues

- Advanced Life Support (ALS) systems are:
  - *Dynamic* – it is not sufficient only to find a single *a priori* setting
  - *Non-stationary* – presence of adaptive organisms such as humans, plants and bacteria as well as degradation requires adaptation
  - *Safety-sensitive* – crew depends on system for life support, verification and validation are important

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Verification and Validation Issues

- Advanced Life Support Systems pose unique V&V challenges
  - Control system needs to detect trends towards failure, which may be months away, in addition to simple failures
  - Verification of models/simulations
  - Modeling of biological processes
  - Distributed control has its own set of V&V issues, especially with respect to timing and communication
- Work-to-date has been in a research setting, so no formal V&V procedures

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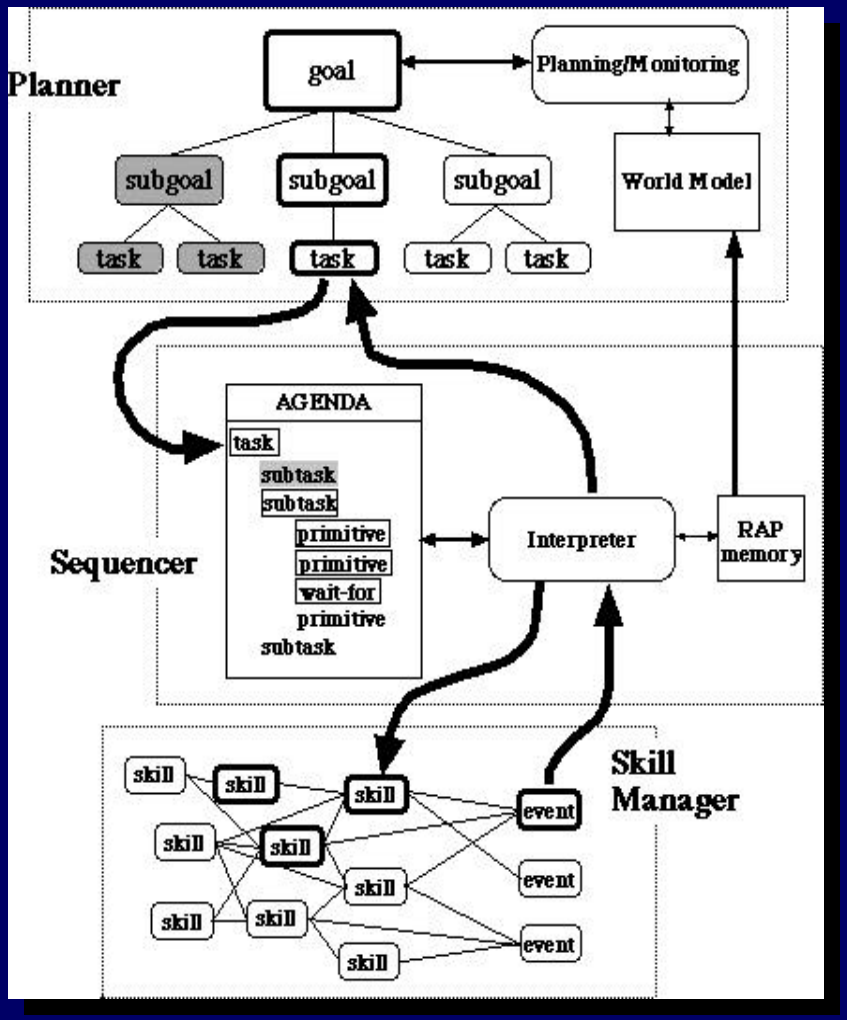
Previous and Current Control Systems

- Several experiments at JSC based on the 3T control architecture
- 3T
  - planning
  - sequencing
  - control



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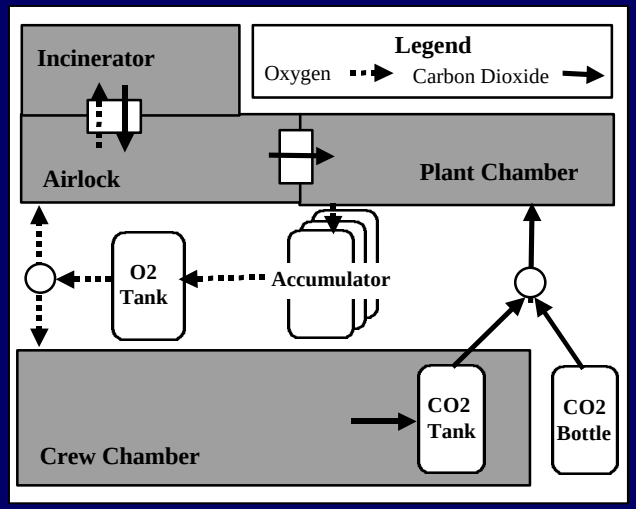
Overall V&V Strategy

- First integrate the lowest tier (skills) with hardware; manually activate low level controls through computer
- Next integrate the middle tier (sequencer) with skills controlling hardware; manual activation of sequences
- Finally, integrate the top tier (planner) with the integrated sequences and skills
- At end of each phase, there is a usable control capability
- Separate skill managers and RAPs for separate control entities

Phase III Crewed Test

- Four crew members for 91 days in a closed chamber
- Wheat crop in another chamber
- 3T managed transfer of gases between the two chambers
- Operated reliably round-the-clock for 73 days (10/6/1997 –12/19/1997)
- Typically ran without human supervision or intervention



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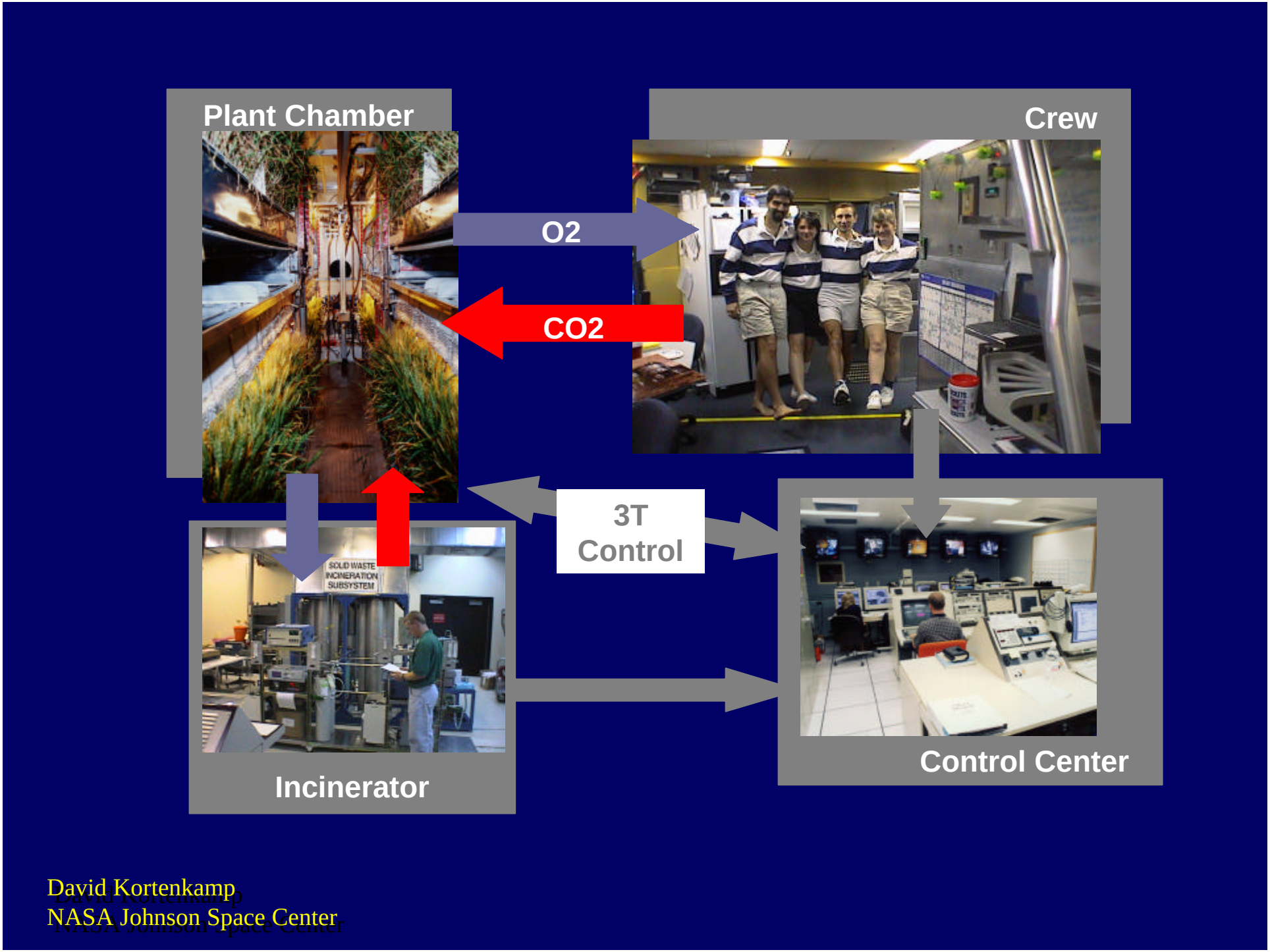

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Verification and Validation

- Phase I
  - Demonstrate feasibility
  - 5 months development, 3.5 months testing (2 programmers)
- Following steps performed in order
  - Stand-alone testing
    - RAPs with emulated skills in lab
    - Skills via user activation in lab
    - Skills with recorded data
  - Interface testing
    - Test data interface between life support DAQ and skills
    - Test RAPS to skills interface using actual data (monitor only)

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Verification and Validation (cont.)

- Phase 1 continued
  - Integrated testing
    - Integrated test of RAPs and skills with hardware during wheat test (advisory only)
    - Integrated test of RAPs and skills with hardware during wheat test (control, only during workday, then 24 hours)

Verification and Validation (cont.)

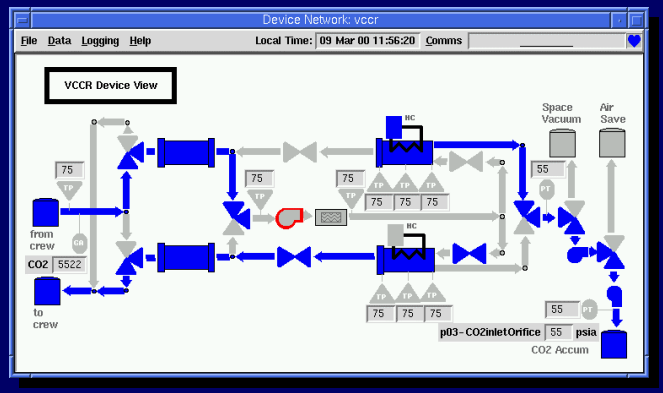
- Phase II
  - Deploy operational system
  - 2 months development, 2 months integration and testing (2 programmers)
- Following steps performed in order
  - Stand-alone testing
    - Emulated skills
    - Test skills with user activation
    - Test skills with recorded data
  - Interface testing
    - Test interface between DAQ and skills
    - Test interface between RAPs and skills
    - Test interface between planner, RAPs and emulated skills

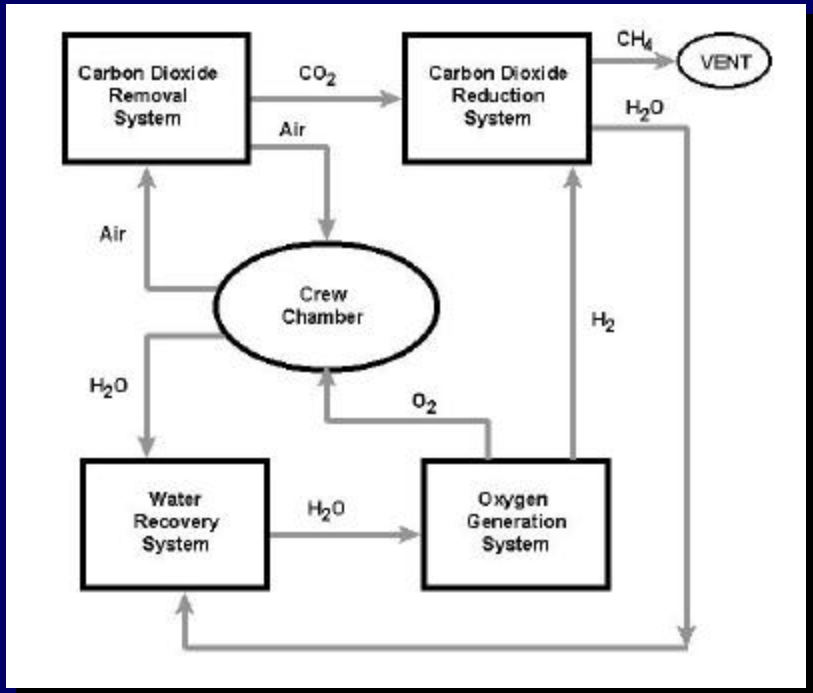
Verification and Validation (cont.)

- Integrated testing
  - RAPs and skills with CONFIG simulation
    - Checked out standard operating procedures
    - Checked out fault management procedures
  - RAPs and skills with actual hardware
  - Planner, sequencer and skills with CONFIG simulation
- Operational testing
  - RAPs and skills for 73 days
  - Planner, sequencer and skills near end of test
- Data recorded including commands and sensors
- See Schreckenghost *et al* IAAI-98

Air Revitalization System

- Simulation of an ARS using a discrete event simulator (CONFIG)
- 3T control integrated with Livingstone MIR (from Ames)
- Planning currently being added





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Verification and Validation

- Stand-alone testing for code validation
  - Skills with user activation
  - Livingstone models with scripts emulating data messages from skills
  - RAPs with emulated skills
  - Planner with sequencer and emulated skills
- Interface testing
  - Test Livingstone interfaces with emulated skills
  - Test interface between CONFIG and skills

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Verification and Validation (cont.)

- Integration testing
  - Integrated testing with RAPs and skills using CONFIG simulation
  - Integrated test of Livingstone, RAPs and skills with CONFIG
  - Integrated test of planner, Livingstone, RAPs and skills with CONFIG
  - See Malin *et al* IEEE Aerospace Conference 2000

Water Recovery System

- Four integrated subsystems:
  - Biological water processor (BWP)
  - Reverse osmosis system (RO)
  - Air evaporation system (AES)
  - Post-processor (PPS)
- 3T skills (over 75 separate skills)
- 3T RAPs
- ~200 sensors and actuators

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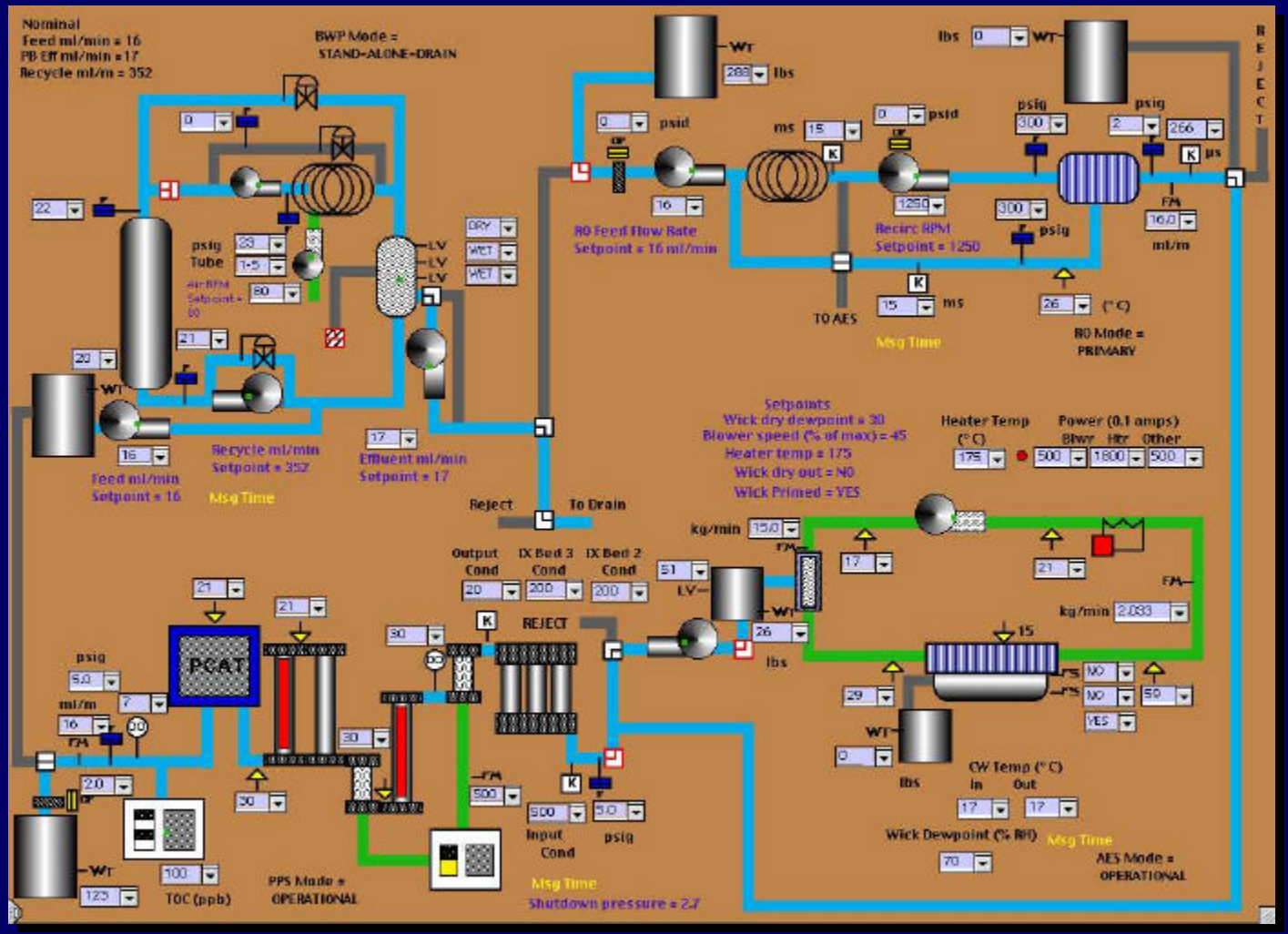
Integration of Subsystems



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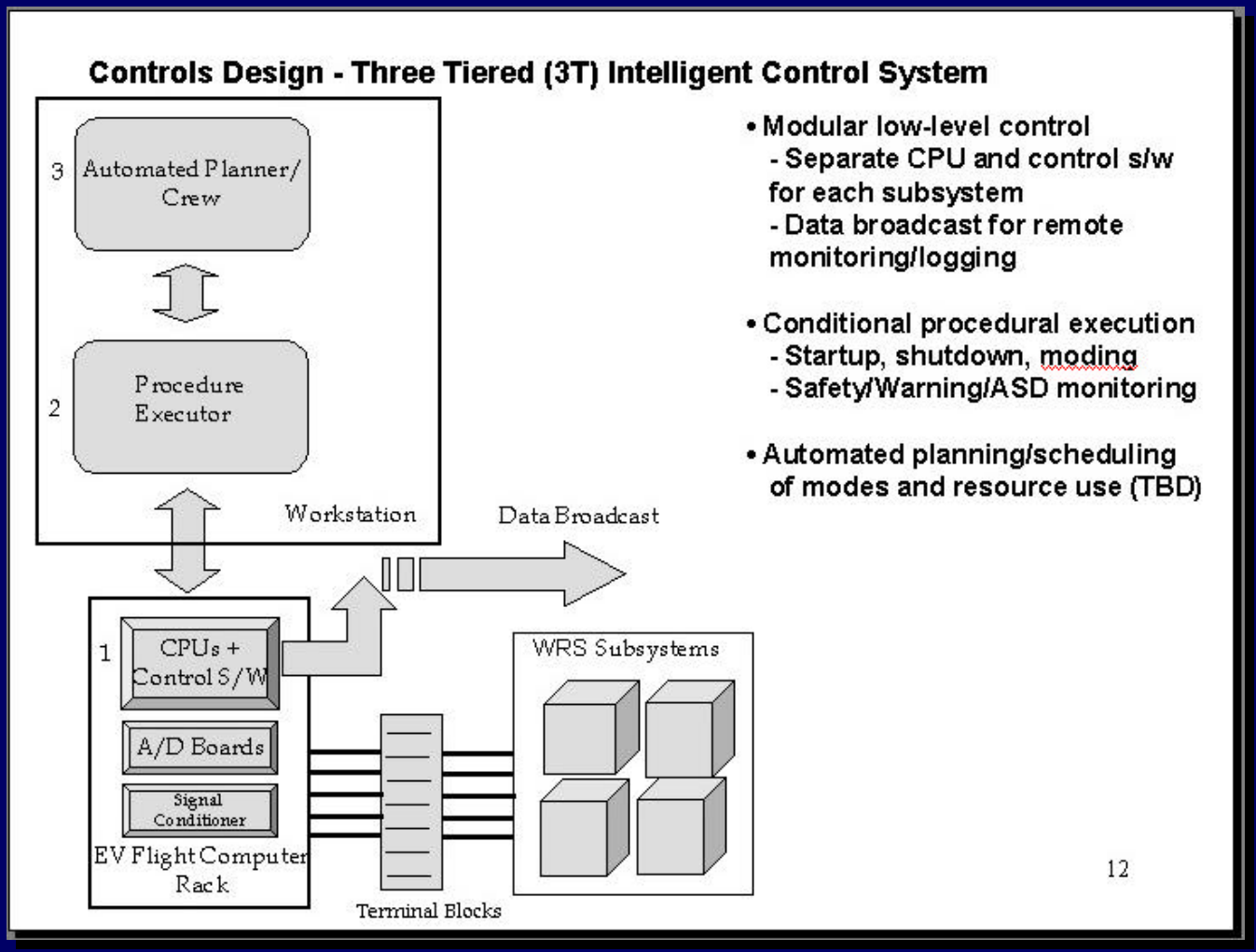
Control Strategy



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Verification and Validation

- Get sequence and state diagrams from design engineers
- Implement code and test with simple simulation
- With hardware, do the following
  - Each subsystem standing alone
    - Calibrate all instruments through the skills
    - Test/verify each low-level RAPs query and action
    - Test/verify each mid-level RAPs
    - Test/verify high-level RAPs
  - Integration tests (using de-ionized water)
    - Test BWP+RO through all test points
    - Test RO+AES+PPS through all test points
    - Test all four systems through each test point
  - Duration: Conduct integration tests for 72 hours

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Verification and Validation (cont.)

- Actual tests (using mix of urine and waste water)
  - Record all data. Analyze off-line daily. Correct control anomalies as necessary.
  - For code changes during test, retest only those portions affected as determined by code inspection and simulation
- Key is that subsystems are treated as independent agents (horizontal modularity) and the layered control gives us vertical modularity
- Pete Bonasso, NASA JSC/Metrica Inc. (see forthcoming i-SAIRAS 2001 paper)

Lessons Learned

- Routine control of complex life support systems is within reach
- Small changes to sensor calibration or the underlying biological/chemical processes requires expensive recoding of control procedures
- Changes to the desired operating regime (e.g., optimizing for a different resource) requires expensive recoding of control procedures
- Complex interactions are difficult to predict
- Adaptation of control code is required for long-duration, autonomous missions

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Learning in ALS Systems

- Most of the control will be hand-coded and fixed
- Some portion will need to adjust as the system runs
- Many open research questions
  - On-line vs. off-line learning
  - Experimentation with the real system
  - Fidelity of models and relationship to learning
  - Abstraction of state and action space (making system aware of hidden states)
  - Crew interaction with learning system (inspectability and instructability)

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The Role of Learning

- Detecting signatures
  - Parsing real-world data stream to recognize events
- Refining models
  - Using feedback from actual system to adjust models
- Robust design
  - Searching through design criteria for optimal solution
- Learning/optimizing sequences
- Integrating with autonomous control
- Adaptive crew interfaces
- Control system design methodology
  - Using learning algorithms to find important variables and interactions
  - Helps overcome some V&V issues since code is hand-written
- Optimizing resource allocation

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ALS State Space

- Potential state space is enormous and hybrid (i.e., mix of discrete and continuous) so we need to abstract
- Possible abstractions are
  - Current levels of consumables (air, water, food)
  - Quality of air and water and health of plants
  - Flow paths for water and air through the system
  - Current energy allocations to subsystems
  - The current phase of operation
  - Crew health/happiness
  - Temperatures and other environmental measures

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ALS Action Space

- Potential action space is large
- Combination of physical actions to produce abstract actions
  - Allocation of energy amongst subsystems
  - Use of consumable stores
  - Crew activity
  - Routing of air/water flows
  - Planting/harvesting of crops (when and which)
  - Adjusting crop light levels
  - Adjusting climate controls
  - Venting of gases to the outside atmosphere

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ALS Rewards and Feedback

- Final or end state rewards
  - Duration of mission with different controllers
  - Total crew productivity over mission duration
  - Total amount of air, water, food or energy available in system or stores
- Progress measures
  - Quality of air and water and health of plants
  - Plant growth rates or plant food output
  - Climate feedback (keeping climate parameters within boundaries)
  - Health/satisfaction of crew

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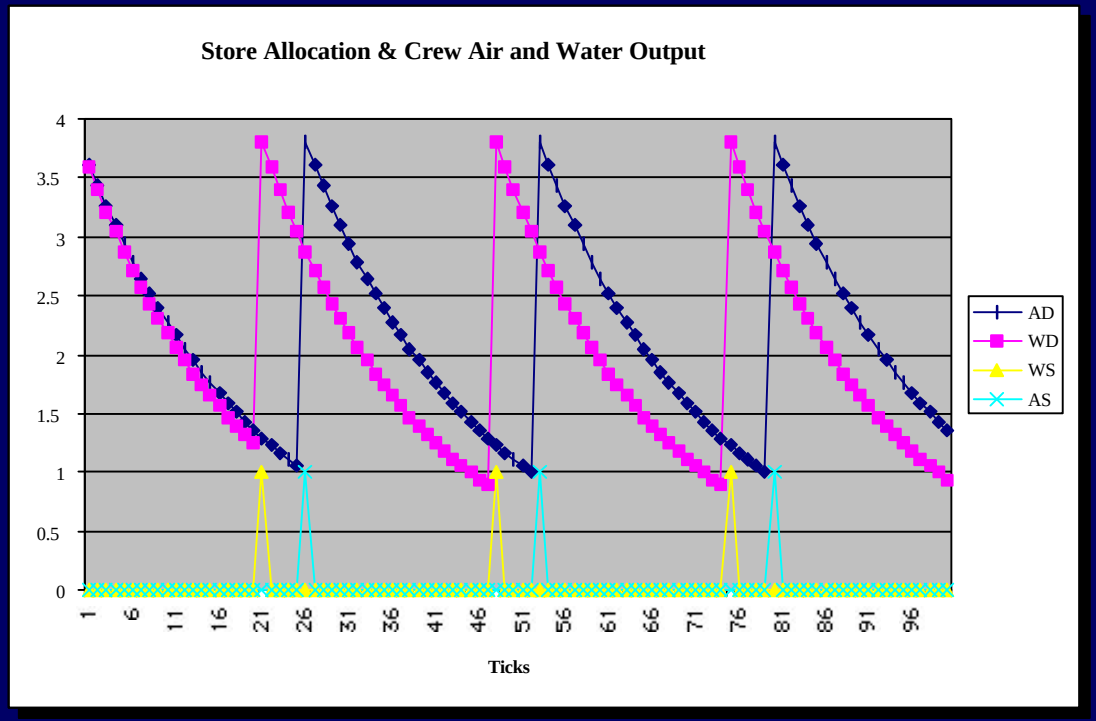
Current Work

- Investigating reinforcement learning and genetic algorithms for optimizing resources
- Have simple simulation



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Future Work

- Begin working on other machine learning application areas
  - Sequence learning
    - Learning contexts as well as sequences
  - Integration with control systems
    - How good does initial control have to be for on-line learning to work?
    - How does control system decide when to devote resources to learning and when to use new knowledge?
- Investigate other ML techniques (memory-based, Samuel)
- Continue to explore theoretical issues of abstraction and model fidelity requirements
- Issue challenge to AI research community and make simulation available to all
- Begin applying techniques to real-world ALS testbeds

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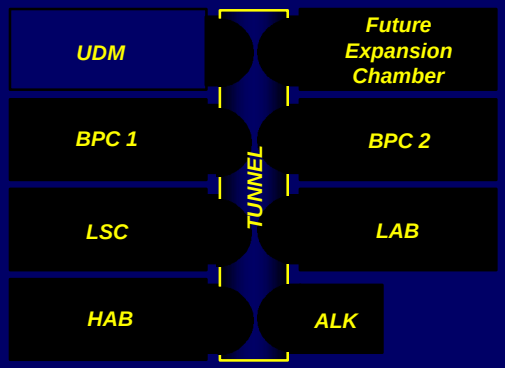
BIO-Plex

- Ground testbed of ALS system being built at NASA JSC
- Crew of 4 for up to 540 days
- 90% of food grown in chambers
- Testing starts in 2004
- Autonomous operation is the goal
- Testbed for future mission ops



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BIO-Plex challenges

- Dynamic system with thousands of sensors/actuators
- Need for mission planning/scheduling
- Modeling biological processes
- Sensor interpretation
- Natural crew interfaces
- 24/7 operation

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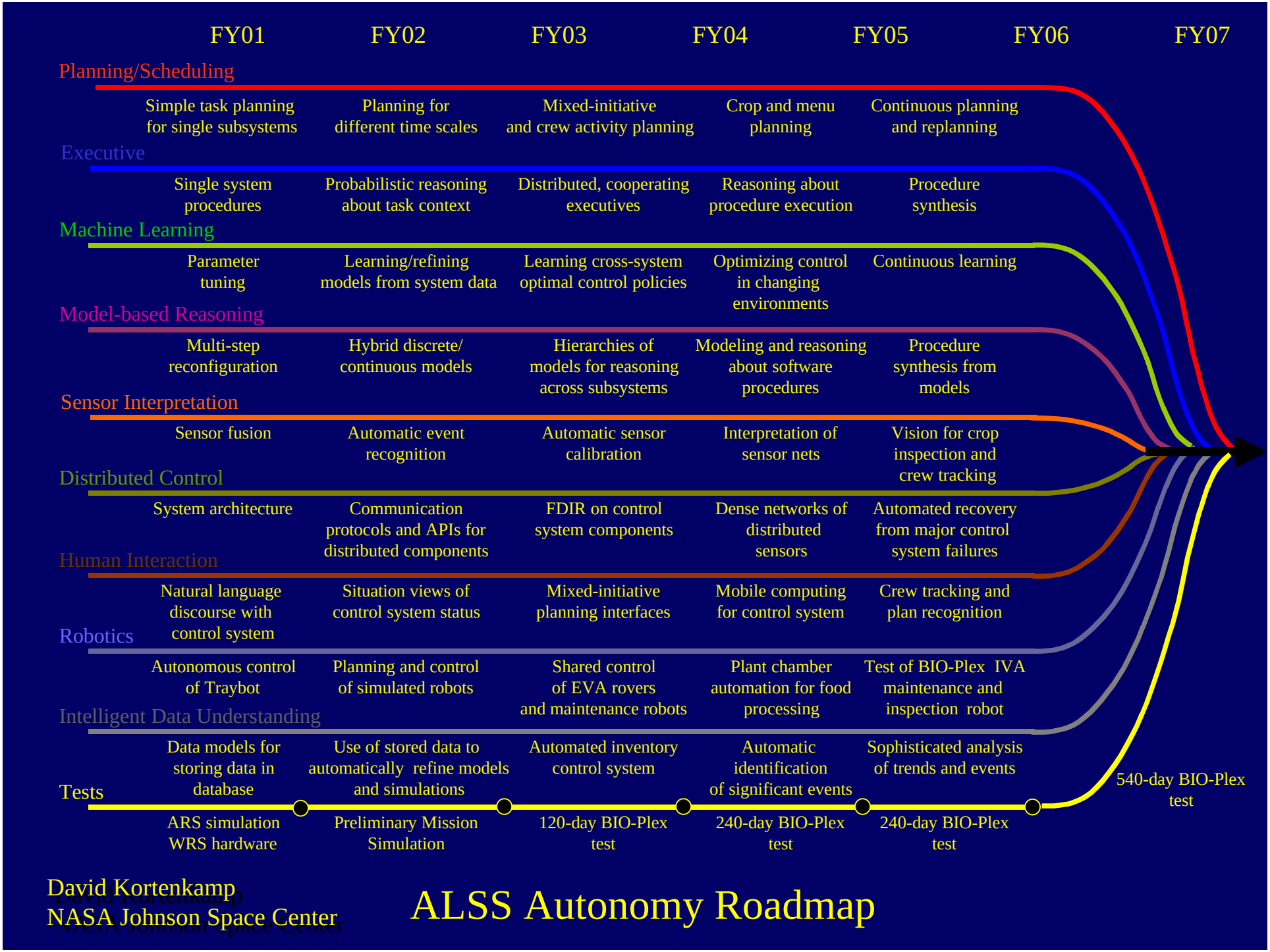

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ALSS Autonomy Roadmap

Conclusions

- BIO-Plex is not a flight system, so we can test advanced concepts in adaptive control and validation and verification
- Tightly coupled, real-time systems that are adaptive will challenge V&V techniques
- Want to move from systems that require extreme crew vigilance to systems that run on their own
  - Still need *adjustable autonomy* see tutorial by Dorais and Kortenkamp on my home page
- Developing a suite of simulations that we can distribute

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