Towards Long-term Reliable Field Robot Operations

Autonomous Systems Laboratory
Queensland Centre for Advanced Technology
ICT Centre
CSIRO
Australia

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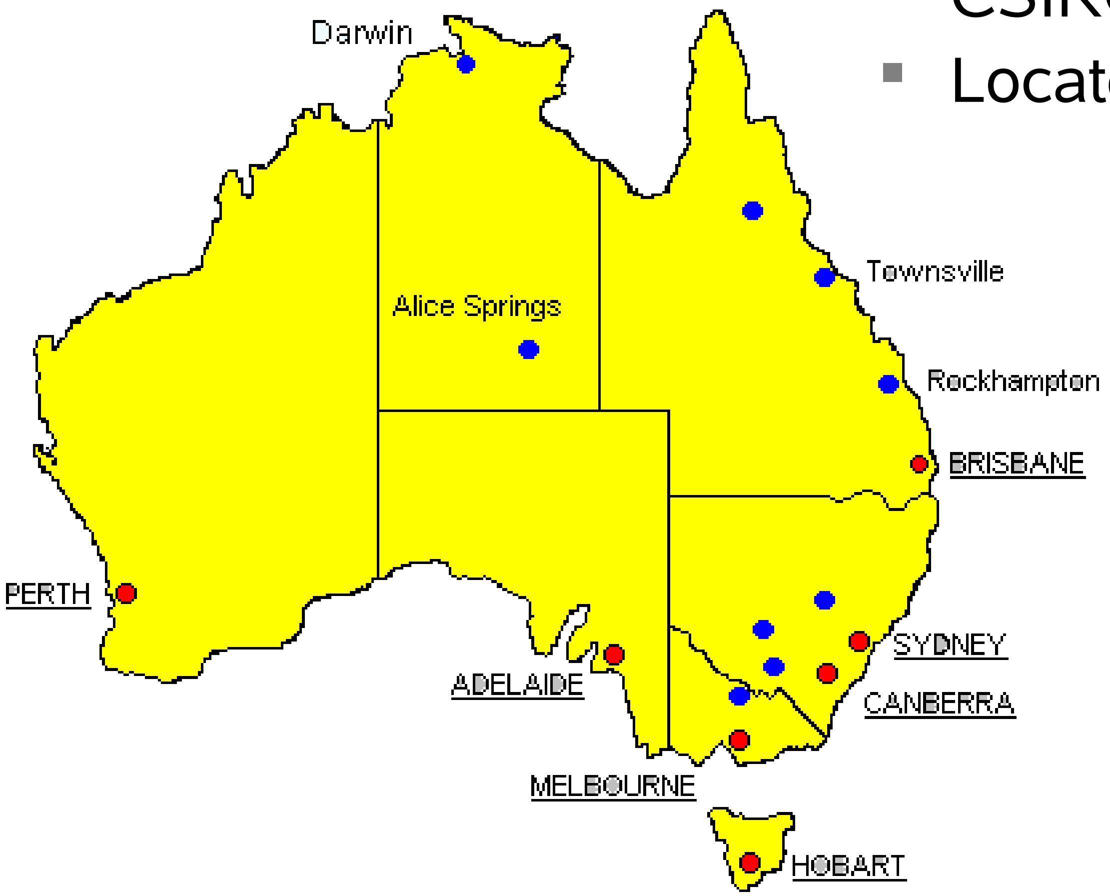
Outline

- Who are we and what do we do?
- Overview our project areas
  - What each entails
  - Reliability and safety
- Underlying principles
  - Hardware dependability
  - Software dependability
  - Task reliability
- Future directions for dependability in field robotics

Who are we?

- CSIRO ICT Centre Robotics group (started in 1994)
- Approximately:
  - 19 staff
  - 4 PhDs
  - 2 postdocs
  - 5 engineering support
- National and international visiting researchers, PhD, Masters and industrial trainees

Where are we?



- We are located in Brisbane
- CSIRO has 6000 staff
- Located at 65 sites

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What we do

- Research and development of autonomous systems for industry and researchers, both nationally and internationally

- Main research projects:
  - mining
  - Unmanned Air Vehicles
  - underwater robotics
  - ground robotics
  - sensor networks

- Aim for reliable, robust and SAFE operations of autonomous systems in commercial and research applications

- Demonstrate competency in everything we do

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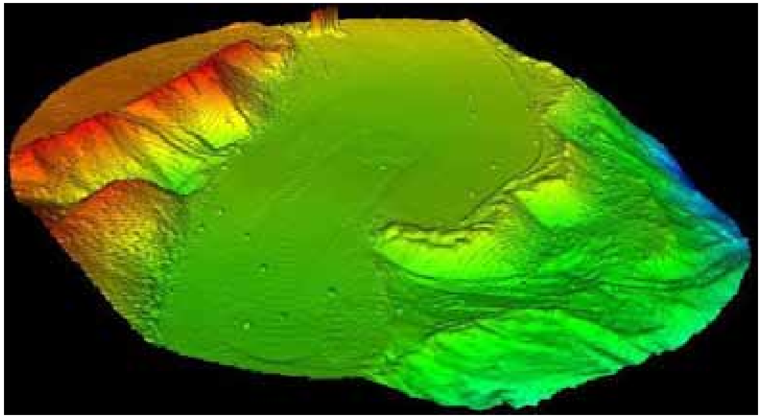
Mining: Overview

- Load Haul Dump (LHD) vehicle for underground excavation
- Dragline - used to remove overburden from a coal seam
- Rope-shovel automation (open-pit)
- Explosives loading in underground mines
- Terrain mapping (for terrain and vehicle loading)
- Traffic control



Mining: LHD automation

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- Demonstrated full speed operation at NorthParkes Mine in 1999
- Size and weight: ~ 10m, 30 tonne, Location: Olympic Dam (South Aus)
- System based upon reactive navigation requiring no guidance infrastructure
- Navigation technology licensed to DAS (CEPL) with commercial system launched April 2003
- Pre-production prototypes developed for three types of LHD including electric machines

1999: Automated CSIRO loader tested at Northparkes mine

2001: Automated Tamrock electric LHD from Northparkes at QCAT

Mining: LHD automation

Mining: Dragline automation

- Draglines are huge machines used to remove overburden
- Weigh approx. 3000 tonnes, 100m boom, cost approx. $60M each
- Location: Callide (Central Qld)
- Work 24 hours a day 7 days a week with a crew of three people
- Since 1994 we have been automating a dragline's cycle (load, swing, dump and return)
- We have installed two systems on production machines

Mining: Dragline Scale Model

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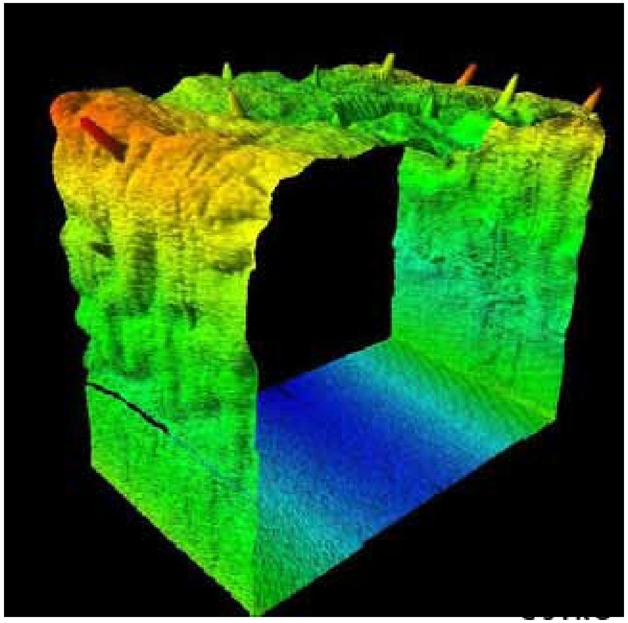
Mining: Rope shovel automation

- Rope shovels are huge machines used to remove overburden or coal
- These machines dig into a bank and dump into waiting haul trucks
- Automation of these machines could lead to significant productivity improvements
- In 2003/04 we demonstrated autonomous digging on a scale model (1/7 th) machine

Mining: Automated explosive charging

- We have developed a robotic charging unit to automatically charge blast holes in underground metal mines
- A scanning laser is used to create a 3D map in order to locate a ring of blast holes
- A vision system is used to guide a hose into the collar of each hole



Mining: Safety – humans in the workspace?

- Mining machines are big and heavy
  - A dragline weighs 3,000 tonnes
  - An LHD weighs 30 tonnes
- Underground mining is particularly hazardous due to confined spaces
- There may be less than 1m between a machine and the walls
- Machines do not even flinch when crushing a person!

Shutdowns

- Can be even more hazardous than start up
- Can mean total machine shutdown or hand back to human
- Could also mean 'go to a safe state' e.g. autonomously navigate to the road's edge
- Emergency stop buttons are located near where people will be
- Shutdown does not necessarily mean turning off power:
  - Power is sometimes required to maintain a machine
  - The power may be needed when operator is trying to recover an emergency (e.g. dragline)

Mining: Reliability and Safety

- Hardware
  - Key access to vehicles
  - Restricted area access to personnel
  - E-stops on and off the vehicles
  - Laser and break-beam sensors where possible (LHD testing)
  - Dead-person switches for semi-autonomous operation
  - External RF link
  - Safety trips – door open, detected system failure etc.
  - Watchdogs
  - External indicators to show machine state. E.g. autonomous or manual mode
  - Indicators at monitor points to show more detailed status
  - INDICATORS ARE EITHER ON OR FLASHING – OFF MEANS BLOWN BULB
- Software
  - Watchdogs
  - Application and sensor-specific integrity checking
  - Different levels of shutdown – E-Stop, graceful degradation etc.

AUV: Autonomous Underwater Vehicle

- Starbug
  - dual stereo cameras, GPS, IMU, pressure sensors
  - 3 flat and 2 longitudinal thrusters
  - localisation by GPS and visual odometry
  - operating depth – 100 m

- Tasks
  - monitoring the Great Barrier Reef
  - environment sensing
  - feature identification and tracking
  - sensor deployment and data muling

AUV: Terrain following

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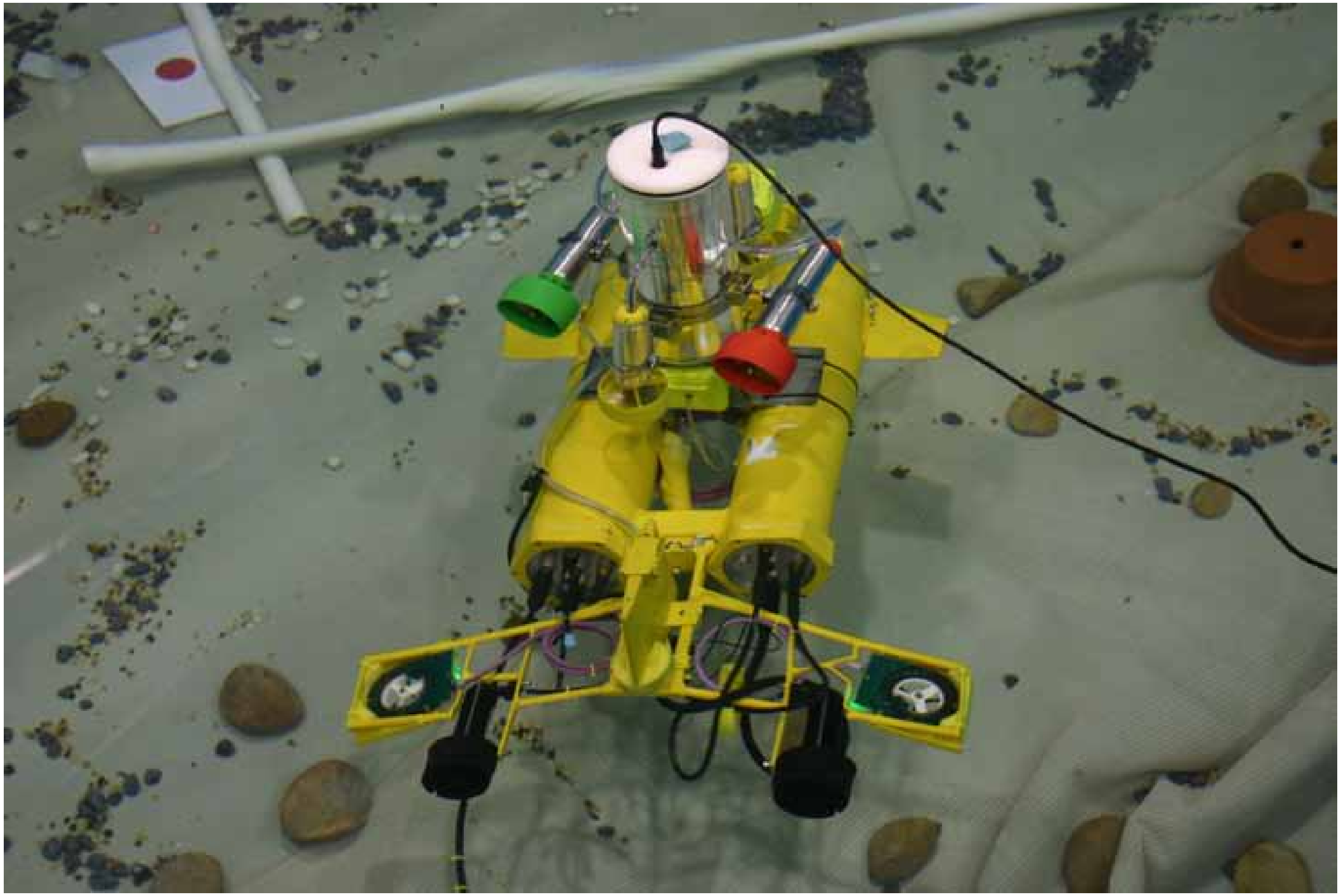
AUV: Cooperative Docking



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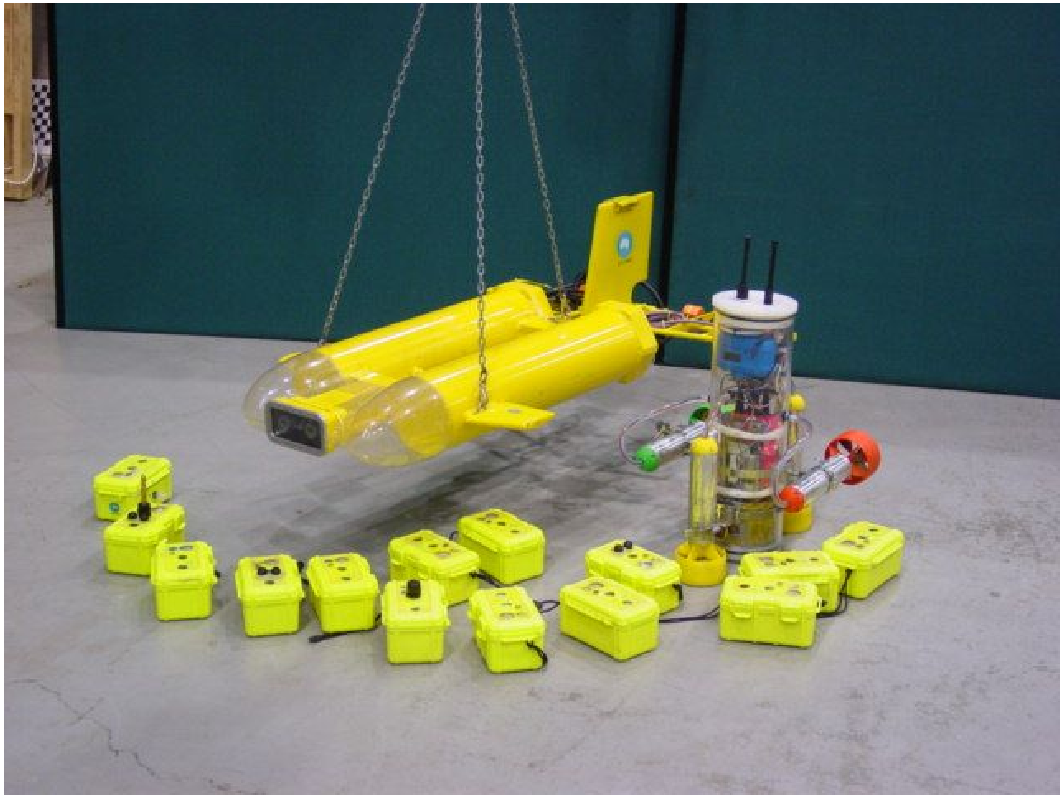
AUV: Underwater Sensor Networks

- Acoustic (broadcast) – 100m 1kbits/s 16bit DSP 10W 20-100kHz



- Optical (data muling) – red/ir leds 320kbits/s 5W 2.4m

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AUV: Safety and Reliability

- Thruster watchdogs from the software controller
- Overspeed/overcurrent protection
- Under and over depth sensors
- Lose power – positively buoyant
- Lose thrusters – controller will still try to achieve goal
- IR sensor for collision avoidance – single bit
- Low maintenance design – few moving parts and hull penetrations

Australian Research Centre for Aerospace Automation (ARCAA)

- CSIRO and QUT initiative that received funding in late 2005
- Research and development of UAV platforms, operations, payloads and certifications for industry operations
- CSIRO research on autonomous helicopter operations
    - common behaviours (e.g. takeoff, hover, landing, navigation, safety to vehicle, infrastructure and people)
    - task-specific behaviours (e.g. environment mapping and sensing, object detection and inspection, deployment of sensors)

Autonomous aerial vehicles

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- Experimental platform for autonomous hovering flight
- Equipped with stereo vision, low- cost inertial sensors, magnetic compass and standard GPS
- Based on a 60-sized hobby style helicopter
- Endurance of approx. 20 minutes
- All computing on-board
- We have developed a vision-based velocity and height estimation system
- Demonstrated autonomous hover in mid-2003
- Safety:
  - Dedicated testing area
  - Fire extinguishers
  - Operator ready for handover during autonomous operations

Mark I (1999-2002)

Mark II – Mantis (2003)

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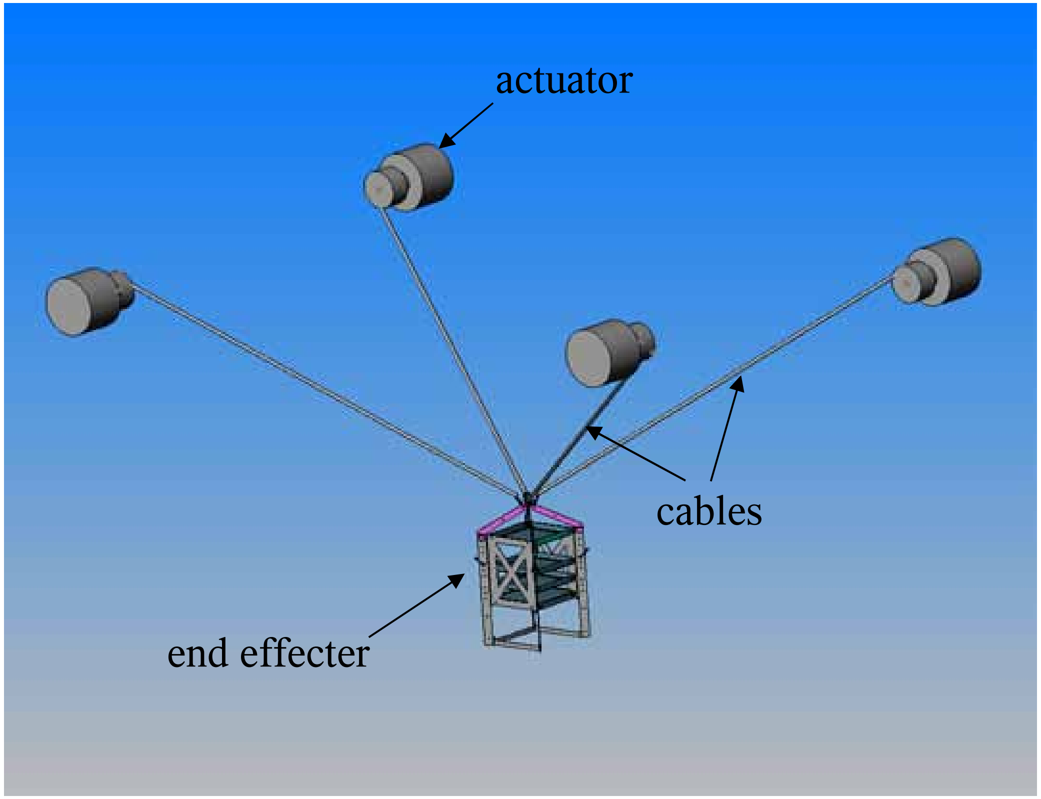
What is a cable-array robot?

- A set of spatially distributed motors which actuate cables connected to an end effecter
  - Similar to a Stewart platform
- By changing the length of the cables, the end effecter can be moved
- Examples include:
  - SkyCam – used in football stadiums for giving an overhead view
  - NIST robot crane
  - Quay cranes



Schematic view of a cable-array robot

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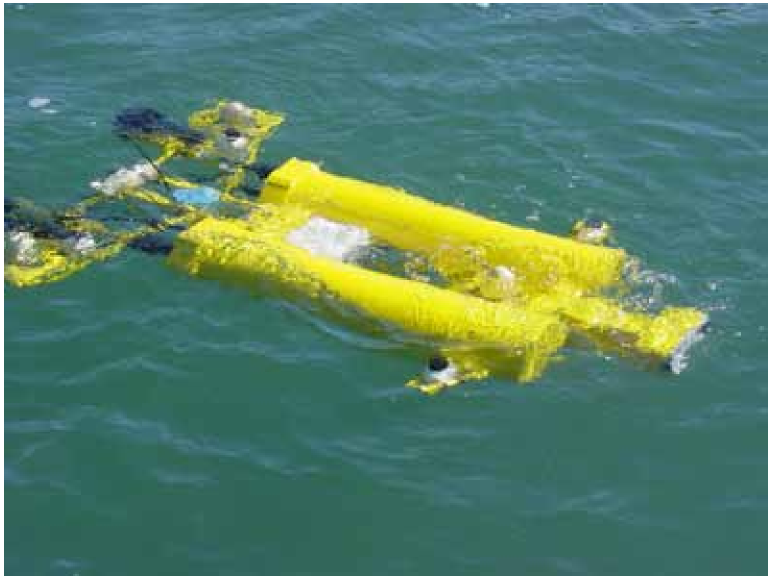
AVS: Uses for a cable-array robot?

- Possible uses:
  - Building, maintenance and monitoring of large constructions
  - Materials processing and handling
  - Clean-up of disaster sites
  - Humanitarian de-mining
- Our use:
  - Simulating flying/swimming vehicles



CSIRO flying and swimming vehicles

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AVS Design

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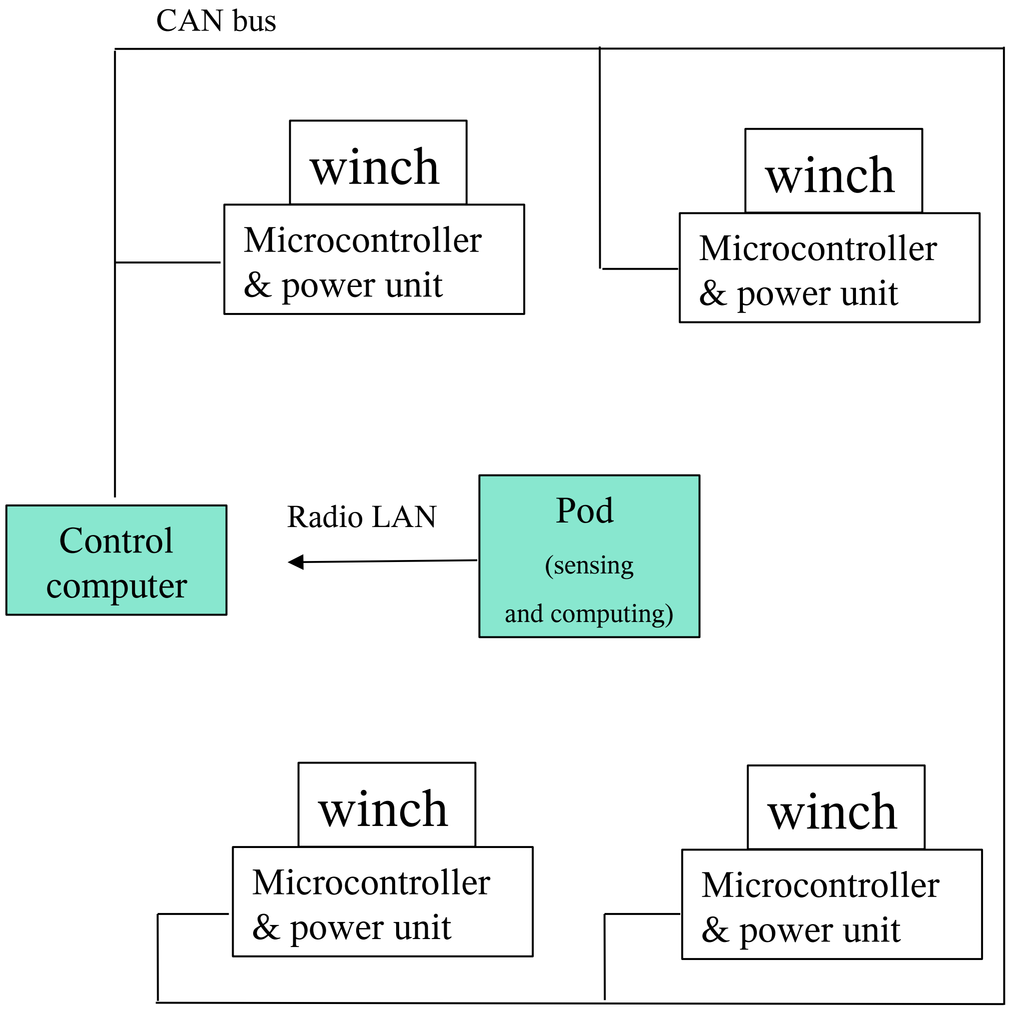
- Safety lock-out system
- Hardware
  - Perimeter monitored by:
    - PLS (laser curtain) on main work-area entry point
      - A robotics group using a PLS for its originally designed function?
    - Line-based lasers on each of the other three work area entry points.
  - E-stops on each winch
  - E-stop at operator station with an automation engage key
  - Monitoring of power and low-level motor drive status
- Software
  - Heartbeat system implemented in the control software
    - On losing this heartbeat – system is shutdown
  - Software e-stop on:
    - exceeding position limits, etc.



AVS control/communication architecture

AVS Design

pulley

winch

HC12/power

E-stop

View of one of the units installed at QCAT

AVS

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Ground Robots: ROVER Project

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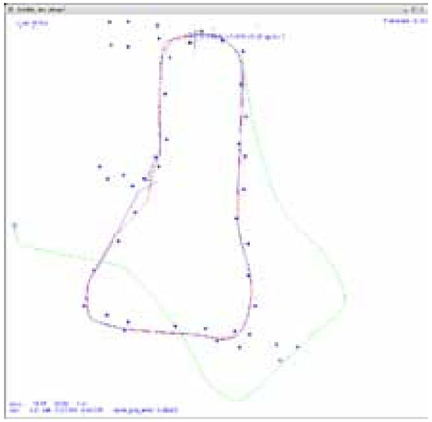
- Navigation, localisation, tasking, safety and reliability around industrial worksites
  - Developing sensor processing techniques – GPS, laser, IMU, vision, WiFi, etc.
  - Vision-based applications - object tracking, feature extraction, colour normalisation, stereo and omni vision
  - Developing application-specific tasks
  - Long-term continuous operations



Hot Metal Carrier (HMC)

- Automating Hot Metal Carrier operations
  - Navigation, localisation, obstacle avoidance
  - Acquiring and dropping off the crucible
  - Safety analysis
    - At our worksite
    - At industrial locations
  - Vehicle reliability
    - Regular maintenance
    - Mandated reporting of anomalies
    - Rigorous testing of automated systems

HMC: Safety - Analysis

Risk Assessment

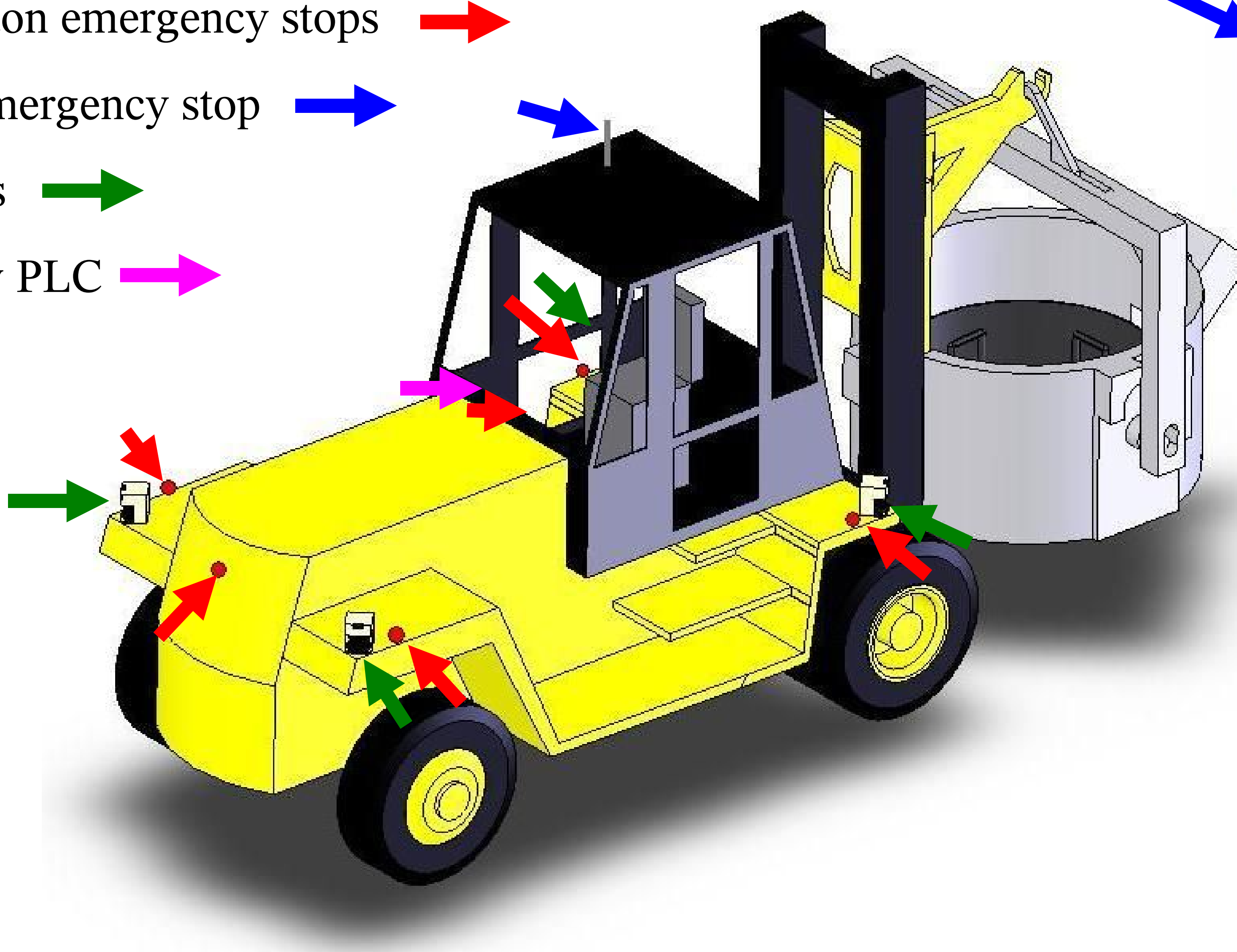
- Speed of Vehicle (>30km/h)
- Weight of Vehicle (17T)
- Pinch points (Crucible, Hook)
- Environmental concerns (Buildings, People, environment)

Identified risks

- Collisions
- Dropping the Crucible
- External factors – Weather, EMI, Other Vehicles, noise, pollution
- Internal failures
  - Brake failure
  - Steering failure
  - Mast failure
  - Loss of Pneumatics
  - Loss of Hydraulics
  - Loss of Electrics
  - Mechanical Failure
  - Control System Failure

HMC: Safety

- 6 Button emergency stops
- RF Emergency stop
- Lasers
- Safety PLC



HMC: Safety - Technical

- This system is a Category 4 safety classification. (Maximum)
  - Two Channel operation, fail to safe with monitoring
- PILZ programmable safety Hardware (Category 4,PNOZ Multi)
  - Monitored Relays (Engine)
  - Monitored Dump valves (Park Brake)
  - Welded contacts check at start up
  - Two channel buttons
  - Manual reset
- All connections are configured so that any loss of Power, Pneumatics, or Hydraulics causes contacts to close to the safe state. i.e. Engine off, Brakes on.
- HBC – radiomatic RF control system (category 4)

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HMC: Safety - Conclusion

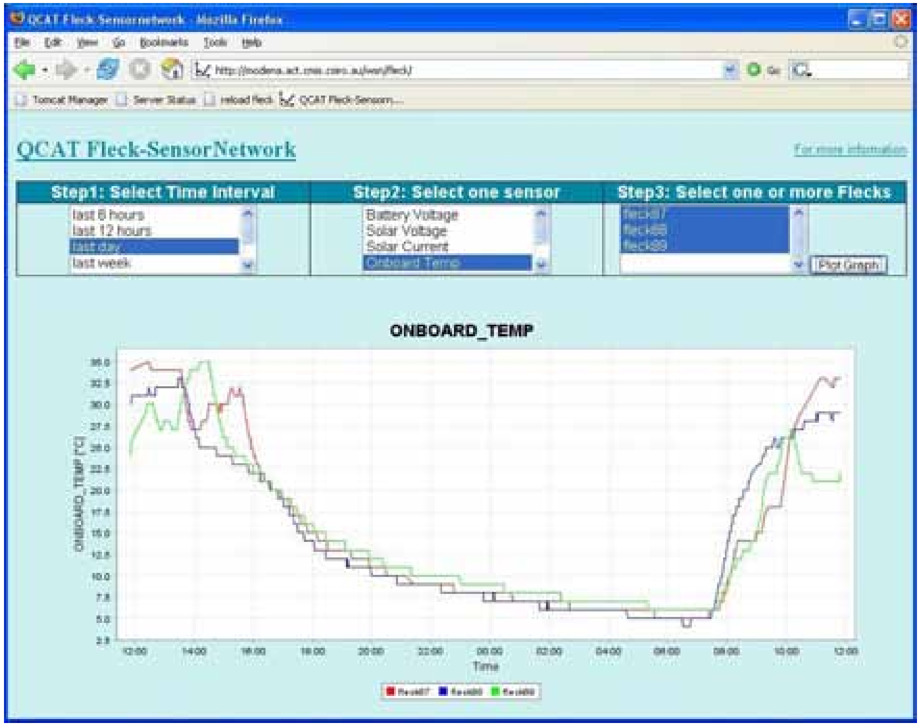
- A computer watchdog signal is used for any computer failures
- Complete safety tests
  - Testing of safety systems and documenting tests
- Safety procedures
  - All autonomous runs are run with a second person with a High visibility shirt in front of the HMC
  - A dead person switch is always utilized on the computer end

Sensor Networks (FLECKS)

- Environment sensing – ambient environment, ground, animal, underwater,
    - Low cost: approx $200
    - Low power: ~mW (2 x AA + solar)
    - Communication range: < 500m LOS
    - Communication bandwidth: 78 kbits/s

- Onboard sensors: battery, solar, temperature
- Environment sensors: GPS, air, land and water sensors
- Actuated sensors - can interact with the environment
- Audio/video DSP info - movement detection and correlation between nodes

FLECK: Network Web Interface



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FLECK: Reliability Issues

- Communications problems
  - Multi-pathing
  - Hidden terminal (a -> b, c -> b, a !->c while c->b)
  - Connectivity
- Waterproof circuitry (conformal coating)
- Dual power sources on outdoor Flecks
  - Solar
  - Battery
- Animal sensors need to be sturdy – cows like to chew or rub them

Safety and Reliability – Hardware, Infrastructure and Environment

- Key access to vehicles and autonomous systems
- Restricted area access to personnel
- E-stops on and off the vehicles
- Laser and break-beam sensors where possible
- Dead-person switches for semi-autonomous operation
- External RF link
- Safety trips – door open, detected system failure etc.
- Watchdogs on systems (e.g. low power can cause unpredictable behaviour)
- Limit restrictions (current, actuator motion, etc.)
- Conformance with relevant OHS&E policies
- Periodic maintenance
- Addressing identified problems ASAP
- Heating, water and dust protection on systems
- Robust design using quality components and techniques – allow access to sub-systems

Safety and Reliability - Software

- Watchdogs
- Application and sensor-specific integrity checking
- Obstacle detection (if objects get too close, bring system to a safe state)
- Version control (CVS)
- Restricted access to core software

Task reliability

How well a robot can *repeatably* perform its tasks. E.g:

- ground truthing performance
- formal analysis of theory
- using probabilistic techniques to allow for uncertainties in operation and the environment
- testing system limits in kinematically accurate simulation
- environment considerations – e.g. how does it operate in light rain?
- extensive testing of the actual systems in a variety of conditions

Safety – too much safety?

- Too much safety can be dangerous?
- Why?
  - Systems with too many safety features tend to be difficult to keep alive (false alarms, more prone to failure, too many components, etc)
  - This leads to people getting frustrated and then disabling or bypassing the safety features in order to improve machine up-time
- In the end the amount of safety incorporated must be a trade-off factoring in acceptable levels of risk and their consequences. This is standard OHS&E methodology
- Safety is not a simple thing to deal with in Field Robots

Future Directions for Robotics and Autonomous Systems Dependability

- Redundancy as much as feasible
  - Sensors
  - Cross validating data
  - Providing a monitoring and retasking system to allow degraded operations
- System health monitoring
  - Subsystems status
  - Heating (computer and platform components)
  - Power levels and usage are within operational limits
  - Noise?
- Long term autonomy testing to investigate and validate developed systems
- Robotics is becoming more widely accepted – it's time to demonstrate highly **reliable** and **repeatable** real robot performance rather than limited successful trials for publication purposes – the DARPA Grand Challenge is a milestone
- This leads to **predictability** of, and **confidence** in autonomous systems by humans

For more information, see www.csiro.au or contact:

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