Terrestrial telerobotic mining technology an enabler for extraterrestrial habitation, mining and construction?

Dr. Greg Baiden
Professor Mining Engineering – Robotics and
Canadian Mining Automation: An Enabling Technology for Space

- The Mining Automation Program (MAP) lead by INCO developed and demonstrated underground mining automation and robotics capabilities (1992-1996) including the automation of over 20 mining systems from drills to LHDs.
- Latencies (teleoperation delays) of 1.5 seconds were typical, and did not significantly reduce operator capabilities.
- Greater than $300M was allocated to this IRAD investment.
- Publication of this work was inhibited to protect corporate advantage.
• Long distance teleoperation with embedded automation

• Technically “Autonomation”
  – One person runs multiple machines with “human touch”
Telemining

• Long distance teleoperation with embedded automation
• Technically “Autonomation”
  – One person runs multiple machines with “human touch”
Key Technologies for Telemining

Telecommunication Network System
Key Technologies for Telemining

Positioning & Navigation Systems

Telecommunication Network System
Key Technologies for Telemining

- Telecommunication Network System
- Positioning & Navigation Systems
- Process Engineering, Monitoring and Control
Key Technologies for Telemining

- Telecommunication Network System
- Positioning & Navigation Systems
- Process Engineering, Monitoring and Control
- Mining Methods

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Key Technologies for Telemining

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- $
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- Telecommunication Network System
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- Mining Equipment

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Key Technologies for Telemining

- Mining Equipment
- Telecommunication Network System
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- Process Engineering, Monitoring and Control
- Mining Methods
- $
• High bandwidth radio network capable of
  – Hardwired communication
  – Wireless communication

• Advantage of Underground
  – Entire radio frequency spectrum is available for teleoperation
Underground Broadband Radio Network

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  - Hardwired communication
  - Wireless communication
- Advantage of Underground
  - Entire radio frequency spectrum is available for teleoperation
Non-GPS Mapping and Surveying
Non-GPS Mapping and Surveying

HORTA - IMU

PLS-Proximity Laser Scanner
Key Technologies for Telemining
Key Technologies for Telemining

- Mining Equipment
  - Process Engineering, Monitoring and Control
  - Positioning & Navigation Systems
  - Underground Telecommunication System
- Mining Process Systems
  - Mining Methods
  - $
Tele- Tunneling
Tele-Production Drilling
Mine Operations Center

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Mine Operation Centers
International Mining Business
Mine Operation Centers
International Mining Business
Mine Operation Centers
International Mining Business

8 Hour Time Zone Shifts

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Mine Operation Centers
International Mining Business

Operation Centers Run Mines and Mine Engineering

8 Hour Time Zone Shifts
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Employees always work dayshift while plant works around the clock

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Potential to supply such low mining costs that other companies mines could be operated for them
SPACE MINING
Lunar Underground Mining and Construction: A Terrestrial Vision enabling Space Exploration and Commerce

Dr. Greg Baiden
Chief Technology Officer, Penguin Automated Systems Inc., Professor – Mining Automation and Robotics, Laurentian University, Sudbury, Ontario, Canada

Louis Grenier
Senior Manager, Space Science and Exploration Planning and Performance, Canadian Space Agency, Montreal, Quebec, Canada

Brad Blair
Vice President of Space Technology, Penguin Systems U.S., Inc., Idaho Springs, Colorado, USA

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SMARTSTEPS Lunar Architecture
MAP Technologies

- The basic fleet to automate mining has been tested and is technically feasible
- These concepts are now being applied at mines around the world
- The techniques form the basis for considering teleoperated lunar outpost construction and lunar mining of water prior to full time astronaut habitation
Assumptions

• Large concentration of $\text{H}_2\text{O}$ found trapped in crater likely at a lunar pole
• Rock types similar to Earth
• 1/6 Gravity
• No water available during initial operations
• No atmosphere available during initial construct of Lunar Base and mine
• Small Scale Nuclear Power Plant installed at site
• Value of Water in LEO substantial and market exists
• Transportation of Equipment and Commodities available at reasonable cost
• Operating personnel initiated construct operation from earth at a Lunar Mining Teleoperation Centre

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Requirements

- Earth Based Lunar Mining Teleoperation Centre
- Lunar Power
  - Nuclear Reactor
- Equipment and Supply Transportation
- Air Lock in side of crater
- High Bandwidth Telecommunication Satellite established in Lunar Orbit
- Four basic pieces of Equipment
  - Delineation Drill
  - Development Drill
  - Digging Machine
  - Explosive Loading Unit
  - Sintering Machine for Ground Stabilization
Economic outlook: A lunar commercial mining forecast

- The space exploration cost equation must be balanced by revenues.
- Future customers for lunar-derived commodities will extend from lunar surface outposts to orbital transportation to emerging manufacturing centers.
- The Moon represents the discovery of a new continent of unexplored land and has significant mineral potential as indicated by its unique geologic features.
Conclusions & Recommendations

- Teleoperated terrestrial mining will gradually become widely applied.
- The Space industry can build on the capabilities being developed in teleoperated mining techniques.
- SmartSteps proposes the construction of an underground outpost to provide humans with a safe haven on the moon free of environmental hazards with the bulk of construction occurring telerobotically from Earth.
- SmartSteps is proposing an analogue site to test the concepts of teleconstruction for a Lunar Outpost.
2010

BREAKTHROUGHS
RESEARCH AND IMPLEMENTATION UNDERWAY
Sub-surface Avionics Systems

- Location of underground equipment
  - Position Location and Navigation System (PLANS)
  - GPS equivalent
    - Currently non existent until now
    - Very Low Frequency Underground Positioning System (VLF UPS)
VLF UPS System

[Diagram showing a VLF UPS System setup with labeled components such as "Atomic Clock," "Equal Length Coax Cables," and "Antenna," along with labeled coordinates "X\_1 Y\_1 Z\_1," "X\_3 Y\_3 Z\_3," and "X\_2 Y\_2 Z\_2." The diagram also highlights a "Base Station."
Initial VLF UPS Application
Conceptual Idea

• Create a dynamic sensing system using synthetic rocks to determine location and path of flow within the rock mass of a block cave operation in real time

• Outcomes
  – Material Flow Monitoring System
  – Underground equivalent of GPS

• Concept Mine testing early 2011
Teleautonomous Applications

• Several independent groups came asking for assistance based on what had been done underground
  – Mining Companies with the problem of Telemining in high altitudes due operator environmental conditions
  – A Mining company regarding underwater mining possibilities, and
  – NASA and the National Science Foundation regarding large scale space construction techniques
Wireless Optical Cellular Communication Concept

- Current wireless radio systems suffer from a lack of bandwidth due to regulations
- Teleoperation systems require significant bandwidth
  - High Altitude Mining
  - Surface teleoperation systems
  - Space systems (Orbiting Space Solar Power)
  - Subsea systems
- Develop a concept that:
  - Is a wireless optical network capable of transmitting/receiving multiple video, monitoring and control channels with high capacity and unnoticeable latency

Patent Pending
Optical Communication Technology
Long Distance Telerobotics for Hazardous Environments
Telerobotic Multi-purpose Robot System

• System consists of
  – Telecommand Trailer with two workstations
  – Robotic Network Construction
    • Communications is done using Long Distance Antennas meshed with short range broad coverage antennas
  – Multiple radio frequencies are employed to deal with the conditions
  – Two Robots
    • Work Robot - Beaverbot
    • Communications Robot - Combot
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Teleoperation Control Centre

- Ethernet linked control centre
- Hemispherical Projected Screen to provide a large field of view
- Embedded Dashboard display
- Configurable Joystick Control
- Common Control Centre for all our Teleoperation systems (submarine, terrestrial, aerial, space)
TeleRobotic Sub TestBed

- Specifications
  - Computational System is a Stealth fan-less computer
  - Penguin developed Robotic CANOpen electronics for all sensor and actuator monitoring and control
  - Battery operated unit
  - Dual Motor Control designed specifically for teleoperation with joysticks
  - IPIX wide field of view cameras
  - Sufficient on-board computer resources to fit side scan sonar or any other devices required
Designed, Constructed and Launched at fully equipped Laboratory on Long Lake in Sudbury

Tri hull Pontoon boat
Large Deck for a pair of Tele-submarines
Electric Winch to Lift and Lower Subs into water
Full Diving Gear for three personnel
On Deck Computer Laboratory for Testing
NASA Rokbot
Long Distance Robot System

• **Purpose**
  – Travel to unsafe conditions to inspect and determine conditions

• **Current work**
  – Travel into a mine 1.5 km where ground collapse is possible, no ventilation and no road maintenance to assess conditions

• **Perform surveying and cavity scanning to assist the client in determining possibility of collapse**
Multi-purpose Robot - Beaverbot

- Six wheeled Skid Steer
- Battery Electric – Diesel Power System
- Penguin Low Latency Electronics
- WiFi Communications for audio, data and video
- Several Arm attachments
Multi-purpose Robot – Beaverbot
Attachments

• Several Arm attachments ranging from grinders to booms
• Grinder attachment to remove safety screen in the drift to allow robot access
• Laser Scanner and arm attachment
Multi-purpose Robot – Beaverbot

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Multi-purpose Communications Robot - Combot

- Six wheeled Skid Steer
- Battery Electric – Diesel Power System
- Penguin Low Latency Electronics
- WiFi Communications for audio, data and video at several different frequencies
- Long Distance WiFi – up to 25km line-of-sight
- Short Haul WiFi – 300 m
- Backup Cable System Ethernet – 1.2 km
Long Distance Laser Scanning Robot System

- **Purpose**
  - Travel to unsafe conditions to inspect

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  - Two Robots
    - Work Robot - Beaverbot
    - Communications Robot - Combot
Advantages

• Extremely accurate mapping for underground environments
• Very fast – the system can do what it would take traditional surveying days to do in hours
• Entire system is battery operated and will fit on any mining cage.
• Information can be directly deposited into any current mine planning system
Uses

• Check surveys
• 3D mapping of drift walls to estimate shocrete thickness
• Calculate the “K” factor for ventilation
• Roadbed surveys
• Finding lost drill holes
Multi-machine Teleoperation System

Teleoperation Work Station

Teleoperation Control System

Wireless Communication System

On-board Robot Control System

Robotic/Telerobotic Machine

Robot Control System

Machine
Nested Multi-machine/Multi-Control Teleoperation System
Diesel/Electric Robot with CMS Scanning Boom
Diesel/Electric Robots
CMS Scanning Boom and Directional and Local Communications Robot
A Bit of History
Path from Human to Robotic Control

Autonomy
Tele-autonomy

Safeguarded Teleoperation
Monitored Teleoperation

Direct Teleoperation
Manual Operation

Robot Initiative

Human Initiative

Human Controlled

Automatic Haulage Truck 1992

Started by trying autonomous operation that worked but was not embraced
Path from Human to Robotic Control

- Autonomy
- Tele-autonomy
- Safeguarded Teleoperation
- Monitored Teleoperation
- Direct Teleoperation
- Manual Operation
- Human Initiative
- Robot Initiative
- Human Controlled

1992
Teleoperation Chairs
putting the person virtually in the
Main Research Project Thrusts

- Teleoperation Control System
  - Visual
  - Haptic
  - Vestibular
  - Audio

- Communication
  - High Bandwidth
  - Low Latency
  - RF, Optics, Hybrid and more
  - Standards (802 IEEE)

- Telerobot
  - Sensing
  - Actuation
  - Intelligence
  - Hardware and Software
Designed, Constructed and Launched at fully equipped Laboratory on Long Lake in Sudbury

Tri hull Pontoon boat
Large Deck for a pair of Tele-submarines
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Virtual Replicator Control System
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Telerobotics Laboratory
- Established in 2002 at Laurentian University
- to experiment with teleoperation issues (latency) and techniques
- a high speed network was established between Laurentian and Cambrian College for experimental purposes
Project Focus Expanded

Underground, Underwater, Terrestrial, Aerial and Space
Teleoperation Chair
Canadian Research Chair Research Team
Main Project Thrusts

- **Teleoperation Control System**
  - Visual
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Tele-submarine with Free Space Optical Communication System
Hemispherical Optical Transceiver

• Transceiver
  – 70 plus LEDs per plate
  – Optical receiver with 120 degree field of view
  – System capability 20 Mb/s/freq
  – Networking Software Protocol Ethernet
  – Current operational capability 1.5 Mb/s due to needing to redefine communication protocols

Patent Pending
Canadian Research Chair Research Team
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Multi-machine Teleoperation of Surface Robots
2\textsuperscript{nd} Generation Model Telerobots
Day 1 - Survey
Day 2 - Survey
Day 1 and 2 Surveys Combined
Underwater Mining and Construction

1) Telecontrol System
2) Specialized High Bandwidth Communication
3) Tele-Robots with limited Autonomy
Canadian Research Chair Research Team
Main Project Thrusts

- **Teleoperation Control System**
  - Visual
  - Haptic
  - Vestibular
  - Audio

- **Communication**
  - High Bandwidth
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- **Telerobot**
  - Sensing
  - Actuation
  - Intelligence
  - Hardware and Software
The Wilson Experiment
The Wilson Experiment
The Wilson Experiment

Task 1 = cleaning nest
Task 2 = grinding food
The Wilson Experiment

Task 1 = cleaning nest
Task 2 = grinding food

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1. Demand or stimulus of a task = $s$

2. Threshold or ability to respond to a demand
1. Demand or stimulus of a task = \( s \)

2. Threshold or ability to respond to a demand
1. Demand or stimulus of a task = s

2. Threshold or ability to respond to a demand
1. Demand or stimulus of a task = s

2. Threshold or ability to respond to a demand
1. Demand or stimulus of a task = \( s \)

2. Threshold or ability to respond to a demand

Elasticity
1. Demand or stimulus of a task = $s$

2. Threshold or ability to respond to a demand

Threshold Model
1. Demand or stimulus of a task = $s$

2. Threshold or ability to respond to a demand

Threshold Model

Tasks = bidding agents

Ants = resources
1. Demand or stimulus of a task = \( s \)

2. Threshold or ability to respond to a demand

Threshold Model

Tasks = bidding agents

Ants = resources

Inspiration

Dispatch system that is capable of adapting to continuous changing operational environment.
A computer (central command) will calculate the response value relative to each agent.

The resource (LHD) is allocated to the agent (drawpoint) with the highest response value at the time of decision making.
Dispatch Decision

A computer (central command) will calculate the response value relative to each agent.

Drawpoints 1, 2 and 3 are competing for this LHD.

The resource (LHD) is allocated to the agent (drawpoint) with the highest response value at the time of decision making.
The Nested Agent-Based Algorithm

Drawpoints

Maintenance Module

Fleet of LHD’s

Teleoperators Fleet
The Nested Agent-Based Algorithm

Drawpoints

Maintenance Module

Fleet of LHD’s

Drawpoints competing for LHD’s

Teleoperators Fleet

Fleet of LHD’s
The Nested Agent-Based Algorithm

Drawpoints

Maintenance module competing for LHD’s and Teleoperators

Maintenance Module

Fleet of LHD’s

Teleoperators Fleet

LHD’s competing for teleoperators
Technology

• The technology was originally built to allow the wireless support of a fleet of Untethered Telerobotic Submarines

• Accomplishments
  – Transmitter/Receiver has been built and tested underwater
  – 1.5 Mb/s tested in fresh water
  – 20 Mb/s tested in the lab
Spherical Optical Communications Technology

Penguin Automated Systems Inc.

The World’s Best Technology Conference 2007
Autonomous vs Teleautomous
After 20 years of doing this in mining the cultural barriers are huge