Innovative Robotic Systems for In-Space Operations

Future In-Space Operations Colloquium
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Dr. David L. Akin
UMd SmallSat Servicing Concept (1990)
Ranger Telerobotic Flight Experiment
Ranger Neutral Buoyancy Vehicle I
Ranger Telerobotic Shuttle Experiment
Ranger Spacecraft Servicing System
Ranger Arms for SUMO Grappling
Ranger Performing HST AI Changeout
On-Orbit Servicing Demand by Types

- Reboost
- Inspection
- Simple Servicing
- Dexterous Servicing

Total Servicing Market ~$3-5B/year
MODSS Dexterous Servicer Concept

- 100 kg-class operational servicer
- Maneuvering spacecraft bus using “green” propellants
- Dual dexterous manipulators with interchangeable end effectors and grappling arm
- Capable of performing at EVA equivalence
- Ideal for operationally responsive dedicated servicing missions
Critical Issues in SmallSat Servicing

- Robotics
  - Grappling
  - Gross manipulation
  - Dexterous manipulation
- Dynamics and control
  - Coupled dynamics
  - Stabilization with robotic motion perturbations
- Operations
  - Low-bandwidth command and control
  - Automation
  - Time delay mitigation
Exoskeleton for Shoulder Rehabilitation

• 5 DOF, capable of lifting itself and subject’s arm in Earth gravity
• Full range and speed of motion equivalence to human
• Designed for rehabilitation of severe shoulder trauma
• Safety-critical redundant control architecture to protect patients
Exo-SPHERES Overview

• Goal was to create a vehicle capable of routine operational use at ISS
• Interchangeable modules fore & aft for mission specific payloads
• Teleoperated from ISS using COTS networking protocols
Advanced Mission Packages (AMPs) are attached to the base vehicle, allowing for more science missions and easy upgrades. Example: Inspection AMP which contains lights and cameras in order to do visual inspections.
Exo-SPHERES with Inspection AMP

- 50 kg freeflyer for ISS external ops
- Advanced Mission Packages (AMPs) for sortie-specific payloads
- CO2 cold gas propulsion with autonomous docking and replenishment
- Developed under DARPA and NASA funding
Exo-SPHERES with Servicing AMP
Sortie Timeline (Base Mission)

Phase 1: Attach AMP
- Inside ISS

Phase 2: Start Up
- C&DH start up
- Run systems checks

Phase 3: Deploy from Kibo

Phase 4: Tele-operation
- Example: inspection mission
- Up to 8 hour duration

Phase 5: Return to Kibo airlock
- Autonomously dock
- Repressurization
Growth Option: Exposed Facility Interface

• Operational issues discovered with Kibo airlock
  – No user-available power or data
  – Airlock envelope is very restrictive in volume
  – Consumables loss with every depress/repress cycle

• Alt recharge/resupply plan
  – Second docking site on Exposed Facility, draws power from station, resupply from attached tanks.
  – Allows external AMP exchange

External Base with CO2 Tanks

External Base with CO2 Tanks and replacement AMPs
Sortie Timeline (External Basing)

Phase 1: Start Up

Phase 2: Deploy from Kibo

Phase 3: Tele-operation

Phase 4: Resupply / Recharge at base
- Change AMPs
- Perform repeated sorties

Phase 5: Return to Kibo for major service/reconfiguration
Exo-SPHERES Protoflight Vehicle

• Exo-SPHERES flight prototype
• Maximum commonality with flight vehicle configuration, electronics, software
• Used for thermal vacuum testing; air-bearing table operation
• Being adapted for parabolic flight testing
EUCLID Neutral Buoyancy Test Vehicle

- Neutral buoyancy version of Exo-SPHERES
- Maximum commonality with flight vehicle configuration, electronics, software
- Allows end-to-end simulation of flight operations in 6 DOF
- Motion capture cameras provide state vector, used to mitigate water drag effects
NEO Mission ExoSPHERES Design

Robotic vehicle for close-proximity navigation, surveying, and scientific investigation around asteroids or comets
DYnamic MAnipulation FLight EXperiment

- Flight experiment to develop and qualify flight control algorithms for free-flying vehicles with significant manipulator disturbances
- 4 DOF manipulator with interchangeable tip masses to alter inertias
- Autonomous operations with periodic downlink to single ground station
- AFOSR UNP-7 program
DYMAFLEX Manipulator Prototype
Exo-SPHERES for Dexterous Ops

- AMP with dual dexterous manipulators, vision system
- Capable of anchor and instrument placement, sample collection, maintenance tasks
- DYMAFLEX manipulator characteristics
  - 80 cm long
  - 7 DOF with interchangeable end effectors
  - 5 kg per arm
Exo-SPHERES Assisting EVA Servicing
DOSS Servicing Flight Demo Concept

- Dexterous Orbital Servicing by Smallsat
- Flight demonstration of servicing tasks
- Self-contained task board
- Autonomous and teleoperated task performance
- Proposed for AFOSR UNP-8
SCAMP End-to-End Servicing Demo

- Smallsat Concept for Advanced Manipulation and Proxops
- Secondary launch on ESPA ring or Dragon
- Self-deploys two cubesats for rendezvous and docking targets
- Performs servicing tasks on surface-mounted task board
- NASA Edison proposal
Proteus Dexteroous Servicing Manipulator

• Evolution of DYMAFLEX manipulator
• Human-scale manipulator
  – 6 cm diameter
  – 1 meter long
• Total mass 8 kg
• Interchangeable end effectors
• 80 N tip force (worst pose)
• >30 cm/sec max tip speed
• Nominal power 75 W
A Sample *Proteus* Toolbox

**Modules**
- Roll Actuator
- Pitch Actuator
- Pitch-Roll Actuator
- Long Arm Link
- Medium Link
- Short Link

**End Effectors**
- Force-Torque Sensor
- Pitch-Yaw Actuator
- High-Dexterity End Effector
- Parallel Jaws
- Handrail Gripper
- Stereo Pan-Tilt

**Nodes**
- Base Node
- Mini-Node

**Free-Flight Module**
A Potential *Proteus* Configuration

Dexterous Arms and Interchangeable End Effectors for Servicing/Assembly

Positioning Arm for Dexterous Manipulators

Free-Flight Module/Stand-Off Video Monitoring Source

Legs for Local Mobility and Stabilization Using EVA Hand Rails
Free-Flying EVA Tool Tender

- Adapted SCAMP free-flying vehicle for EVA support
- Carried EVA tool board for simulated crew activities
- Reduced crew time required for translation, tool handling
- Minimizes use of valuable “real estate” on front of suit for tool storage
- Provides external view of EVA operations
Astronaut Restraint and Mobility System

- Tether cables secured into asteroid surface at disparate locations
- Three cables provide restraint and down-force for locomotion
- Active tension control and real-time navigation data
- Theory developed for adaptive control implementation
ARMS Experimental Verification

- Test subject in microgravity (neutral buoyancy) restrained with three constant-force tethers
- Verified locomotion on underwater treadmill
- Motion capture cameras documented gait
- Tests demonstrated basic feasibility of concept
EVA/Robotic Servicing of HST
Robotic Augmentation of EVA (from SM1)

EVA Daily Average from SM1

Time (hrs)

0:00 3:00 6:00 9:00 12:00 15:00 18:00

EVA Day 1 EVA Day 2 EVA Day 3 EVA Day 4 EVA Day 5

Legend:
- Rangers (pre-EVA)
- EV1 - with Ranger
- Rangers (during EVA)
- EV2 - with Ranger
- Rangers (post-EVA)
EVA/Robotic Servicing for Future S/C
CEV Servicing with Logistics Pallet
Suit-Integrated Manipulator
Power-Augmented Suit Glove

- ILC-Dover designed EMU glove with MCP joint
- UMd added robotic actuator for MCP joint, control system to follow hand movements
- Reduced force required for MCP actuation from 16 pounds to 12 ounces
- No penetration of pressure bladder (all actuators, sensors, and controls external)
Morphing Space Suit

• Initial focus on morphing upper torso ("MUT")
• Linear actuators in restraint wires to control position and attitude of neck ring, shoulder bearings, waist ring
• Analytical approach: four intercorrelated Stewart platforms
• Nonideal effects of pressurized fabric on wire runs
• Extended to power-assisted arm segments
Powered Suit Concepts ➔ SuperSuit

- Hard suit (AX-5 shown here) as notional starting point
  - All rotary joints
  - Rigid structure for actuator integration

- Use body joint angle sensors for actuator command inputs

- Provide hard stops to protect wearer

- Start with augmentation; evolve to amplification
Possible Applications of a SuperSuit

- In-flight EVA training - suit as haptic display device
- Control-mediated operations - limiting velocity, energy input, increasing human accuracy
- Human workload reduction - commanding suit to hold tool in hand, position in foot restraints
- Controllable compliance - select rigidity for microgravity foot restraint activities
- Autowalk - reduce crew workload for mobility
- Integrated short-range flight capability - “jump jets”
- Self-rescue - suit returns to airlock if wearer is incapacitated
- Goal: Make the human more capable than in shirtsleeves
Space Utility Vehicles

• Single-person spacecraft for extravehicular activity
  – Suit helmet and arms provide human dexterity and vision
  – Robotic manipulators for capture, instrument placement, positioning

• Provides rigid structure as protection against shifting aggregate, radiation, MMOD

• Free-flight capability in crewed and autonomous/teleoperated modes
SUV Design Study Assumptions

- Single-person spacecraft
- Suit arms, dexterous robotics, and grappling arms
- No suit or suitport
- Dual SUV sorties for reliability
- Transport two crew in contingency
- Dual docking interfaces
- 10-12 hour sorties
Safety Implications of Dual SUV Sortie

- System failure
  - Life support functional
    - Second SUV docks and transports to base
      - Second docking port required for crew egress
  - Life support nonfunctional
    - Bail out in space suit
    - Issues of environment, suit life support duration, first aid, transport to base
    - Transfer to second SUV
      - Pressurized volume sized for two crew (contingency)
- Crew incapacitated
Potential SUV Mission Applications

• Commercial LEO servicing
  – Launch in Dragon extended trunk
  – Would require matching docking interface on Dragon
  – Supports dedicated servicing missions

• International Space Station maintenance
  – Launch in Dragon extended trunk
  – Would require docking interface adapter on CBM
  – Two SUVs needed for safety
  – Allows contingency external operations without prebreath
Potential SUV Mission Applications

- **GEO servicing**
  - Can be equipped with radiation shielding for GEO environment
  - Allows human/robotic servicing of critical assets
  - Potentially profitable method to extend human presence beyond LEO in near term

- **Asteroid/comet missions**
  - SUV provides protection against unknown environmental hazards (e.g., loose aggregates)
  - Free-flight capability provides positional control in microgravity environment
  - Does not require cabin depressurization for EVA
Potential SUV Mission Applications

• Deep Space Habitat support
  – Additional radiation protection
  – No prebreathing
  – Additional capabilities in communications (DTE)
  – Supports servicing across developing infrastructure at L1/L2/low gravitational gradient sites of interest

• Other application domains?
SUV as Exploration Augmentation Module

- Launched with robotic retrieval mission
- Provides support for crew visit
- Dual Orion docking interfaces
- Serves as both conventional airlock and suitports
- Provides independent free-flight mobility, EVA support as mini-MMSEV
- Capable of robotic exploration and support tasks prior to crew arrival and after departure
Closing Thoughts

- The problem with space robotics is that it has developed its own mythology through the years
  - “If I say my program needs a robot, I’ll have to pay for it”
  - “There’s no way a robot can do what an astronaut can”
  - “To develop and fly a space robot, you have to have already developed and flown a space robot”

- Highly capable (EVA-equivalent) space robots can be made compatible with ESPA secondary launch

- Small robots are lower in cost, and enable a business case to be made for single-target, expendable servicing missions
More Closing Thoughts

• Highlander myth: “There can be only one.”
  – Robots are not generalists; there are niches for a rich ecosystem of space robots
  – Not every task is optimally performed by a humanoid
  – Only one robot → feature creep → cost growth → longer planned lifetime → higher reliability → cost growth...

• If humans will always be the most expensive element in space, use robots to make them as capable as possible

• The robotics field is vastly bigger than NASA, or even the U.S. players → opportunity and peril