The Berkeley Aerial Robot Project (BEAR)
http://robotics.eecs.berkeley.edu/bear

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University of California, Berkeley
Berkeley BEAR Fleet: *Ursa Minor3* (1999- )

- **Boeing DQI-NP** on gel mounting
- **GPS Card**
- **GPS Antenna**
- **Wireless Modem**
- **Radio Receiver**
- **Navigation computer**

**Specifications:**
- **Length:** 1.4m
- **Width:** 0.39m
- **Height:** 0.47m
- **Weight:** 9.4 kg
- **Engine Output:** 2.8 bhp
- **Rotor Diameter:** 1.5m
- **Flight time:** 15 min
- **System operation time:** 30 min
Berkeley BEAR Fleet: *Ursa Maxima 1* (2000- )

Based on Yamaha RMAX industrial helicopter

- Length: 3.63m
- Width: 0.72m
- Height: 1.08m
- Dry Weight: 58 kg
- Payload: 30 kg
- Engine Output: 21 hp
- Rotor Diameter: 3.115 m
- Flight & system operation time: 60 min
BEAR Fleet: rotorcraft

- **Ursa Magna 1, 2 (June 1999~present)**
  - Advanced navigation & control algorithm development
  - Multi-agent scenarios, formation flight, Vision-based landing

- **Ursa Major 1 (Nov. 2002 ~)**
  - Low-cost, high-payload platform
  - Aggressive Maneuver, Vision-based landing
  - Multi-agent scenarios, Model-predictive control

- **Ursa Electra  (July 2003~present)**
  - Fully autonomous electric helicopter
  - First-hand test vehicle for advanced concepts

- **Ursa Maxima  (July 2000~present)**
  - High-payload platform
  - Multi-agent scenarios, formation flight, obstacle avoidance
Berkeley BEAR Fleet: *Ursa Maxima 1*

- **Laser Range Finder**
  - Modified light weight scanner
  - Maximum Detection Range: 50m

- **Flight Controller:** ADL P3
  - Pentium III 700MHz
  - QNX RTOS

- **Motorized scanner**
  - tilt mount

- **Wireless Communication**
  - Short Range: Wireless LAN
  - Long Range (up to 30mi): Wireless Modems

- **Inertial Navigation Sensor**
  - CMIGITS-II
  - IMU+GPS
  - 100Hz Update

- **GPS:**
  - Novatel OEM4
  - 2cm StDAccuracy
  - 20Hz Update

- **Ground Control Station**
  - Laptop/PDA
  - Windows XP/Windows CE

- **Berkeley BEAR Fleet:** Ursa Maxima 1
Mobile Ground Station

- Agent monitoring/commanding
- Full duplex voice communication
- DGPS broadcasting
- Auto-tracking video camera w/ recording
- Wireless video reception
- Weather station
- Hoist
Hand-held UAV Interfaces

Mobile Access and Command Extension (MACE)
- "fly-by-fingertip" operation using touch screen
- minimal obscurity monocle display
- Real-time vehicle location & status monitoring
- Waypoint programming
Experimental Results: Pursuit Evasion Games with 4UGVs and 1 UAV (Spring’ 01)
Pursuit-Evasion Game Experiment

PEG with four UGVs
  • Global-Max pursuit policy
  • Simulated camera view
    (radius 7.5m with 50degree conic view)
  • Pursuer=0.3m/s Evader=0.5m/s MAX
Flight Test: UCB PEG “Rules”

- Max 20 min. games:
  - Evader goal: get to final waypoint or avoid evader
  - Pursuer goal: ‘target’ evader
- Pursuer and evader restricted to same performance limits
  - reliant on F-15 pilot’s cooperation
- Planes on the same logical plane, but separated by 6000ft altitude at all times
  - After first PEG, F-15 pilot request this be reduced to a 2000ft altitude separation
- Two scenarios:
  - UAV as evader
  - UAV can become pursuer
UCB PEG Experiment #1 Test Plan: UAV as Evader

• UAV attempts to cross Scenario Area from East to West without being targeted by the F15
• UAV “wins” by:
  – Reaching the RVPT
  – Not being targeted for 20 minutes
• F15 “wins” by targeting the UAV
• Note: F15 performance is restricted
UCB PEA Experiment #2 Test Plan: UAV as Evader and Pursuer

• UAV attempts to cross Scenario Area (SA) from East to West without being targeted by the F15, however, UAV will attempt to target F15 if suitable conditions arise

• UAV “wins” by:
  – Reaching the END ZONE
  – Not being targeted for 20 minutes
  – Targeting the F15

• F15 “wins” by targeting the UAV

Note: F15 performance is restricted
Flight Test: Experiment 1
Experiment 2: T-16 is evader and pursuer
Vision-based Landing of an Unmanned Air Vehicle

Omid Shakernia, Chris Geyer, Todd Templeton, Jonathan Sprinkle and Mike Eklund
Hardware Configuration

On-board UAV

Vision System
- Vision Computer
  - Camera
  - RS232
  - WaveLAN to Ground
  - Frame Grabber
  - Vision Algorithm
  - RS232

Navigation System
- Navigation Computer
  - INS/GPS
  - RS232
  - WaveLAN to Ground
  - Control & Navigation
  - RS232
1. Previous estimates and inertial data are fed into system

2. Motion compensation of previous estimates using inertial data

3. Features tracked and disparities estimated

4. Motion estimated from sparse features

5. Estimate dense ground elevation map (measuring apparent parallax w.r.t. ground plane)
Transition to Maverick aka Renegade (A-160 surrogate) platform

Modified Robinson R22

UCB Autonomous Vision Landing System
- Navigator
- Map-builder
- Vision subsystem

Maverick avionics package
- RT CORBA based OCP interface
- Input / control: $u_t$ (e.g., waypoints)
- Output / state: $x_t$ (attitude, position, speed)
- Low-level flight controller
- GPS & INS

Real-time Operating System

Other OCP Applications

OCP interface
- Output to avionics: $u_t$ (waypoints)
- Input state: $x_t$ (e.g., speed)
- Provide terrain map to clients: $h(x,y)$
A-160 Hummingbird landing: Surrogate is Maverick: R-22
3D Terrain from Parallax: Results Dec 2005

- Terrain elevation and appearance recovered from flight simulated near Victorville, CA airport
- Path of vehicle super-imposed on map
- 5 meter average error at 1500m AGL
Navigation Output Viewed from Boeing’s OCP Controller Feb 2006
Two R-50s are programmed to fly head on into each other. The Nonlinear Model Predictive Controller chooses a trajectory to cause them to deviate from the nominal trajectory and fly past each other safely.
Conflict Detection and Resolution

Berkeley UAV
Collision Avoidance
Experiment

David H. Shim, H. Jin Kim
May 25, 2003

University of California, Berkeley
Autonomous Coordinated Flight

Hoam Chung, Elaine Shaw, Karl Hedrick and Shankar Sastry
Intelligent Machines and Robotics Laboratory

University of California, Berkeley
**Experiment Scenario**

Virtual leader running on a laptop

Virtual followers running on laptops

Real RUAVs
Formation Flying with 2 real and 7 virtual UAVs November 2002
Transition to 160th SOAR, Ft. Campbell, KY and Ft. Rucker, AL

- In many practical situations, a helicopter team is formed by heterogeneous vehicles
  (ex. Little Birds + Blackhawks + Chinooks)
- In-flight formation joining/reconfiguration procedures are extremely dangerous
- Autonomous aerial refueling will be a great help
- The effects of battlefield stress exerted on aircrew increases dramatically under tight formations and in adverse circumstances

New suggestion: Model Predictive Control
- Implementation issues
  - Communication
  - Pilot/controller interaction
  - Initiation/Termination of a formation
  - Interrupted by hostile event
Simulation of formation split and rejoin for 160th SOAR
Formation Manager

Simple FSM for emergency break up/rejoin

Formation

- Normal
  - As the last follower
  - Operator escape/too small gap
  - Gap error small enough

Single

- Away from the formation
- Normal
  - Sufficient spacing
  - Rejoining requested
- Approach to the formation
Obstacle Avoidance using Model Predictive Control and A Laser Scanner

David Shim, Hoam Chung and Shankar Sastry
NMPC in 3-D complex environment

• The nearest point of the surrounding buildings found
• The obstacle weighting function is applied.
• Receding horizon approach is advantageous than potential function approach when the helicopter stuck in deadlock
NMPC in a Complex 3-D Environment

Potential function

NMPC
Obstacle Sensing using Laser Scanner

Scanner

Control Computer
- PIII 700MHz PC104 module

Tilt Mount
- Encoder
- Servo
- Micro controller

Ground Station
- Real-time 3D Visualization

Flight Computer
- GPS+INS
- PIII 700MHz PC104 module

MPC Engine
- Real-time optimization

Light weight
2D Laser Scanner
- 361 meas/scan

Position Command
Encoder reading
Measured range data
Vehicle state

Reference trajectory
Navigation data
Minimum range data
Visualization of Real-time Local Map Building Process
Urban Flight Experiment

- 6 canopies to simulate urban environment
- Secured by stakes at four corners
- Resistant to wind gust of rotor downwash
- Sufficient distances each other for helicopters to fly through

Richmond Field Station, UC Berkeley, Richmond, California

10’ X 10’ Easy-up Canopy
New Platforms: BEAR Coaxial UAVs

Length: 1.2 m   Width: 0.35m
Height: 0.7m    Weight: 8.2 kg
Rotor Diameter: 1.5m
Flight time: 20 min
System operation time: 90 min

GPS Antenna

Avionics
Nav-computer
GPS receiver
Wireless comm

• IMU on vibration isolation mount

Small coaxial UAV for indoor operations: 1 lb payload
New Vehicle Platform: Tankopter

Aerobotic vehicles will need to have micro-maneuver capabilities.
SMART BIRD
Single-Man Aerial Reconnaissance Tool:
Battlefield Information Recon Deployment
UC Berkeley, S. Shankar Sastry, PI

Single operator, stealth, back-pack size, hand launch/recovery, modular, 48” electric-powered wing, 2.5 lb UAV (1 lb payload), 2-mi. range, loitering ability (day/night) without GPS, autopilot (wing leveler & altitude hold), 2.4 GHz video/data downlink, requires no tools for assembly/disassembly
Smart Bird takes flight

Smart Bird

“Single Man Aerial Reconnaissance Technology
Battlefield Information Reconnaissance Deployment”
BEAR UAV Research Test bed: A Legacy of Innovation and Transition

- Architecture for multi-level rotorcraft UAVs 1996- to date
- Pursuit-evasion games 2000- 2002 (transitioned to AFRL/Darpa/Boeing UCAV program)
- Vision Based landing on pitching decks 2001- to date (transitioned to Socom Boeing-Frontier Systems Maverick/A-160)
- Multi-target tracking 2001- to date (transitioning to 1st MEP, Camp Pendleton)
- Formation flying and formation change 2002-4 (transition begun to Army Socom, 160th SOAR, Sikorsky)
- NMPC Based Acrobatic Flying, conflict resolution 2003 (transitioned to DARPA UCAR, Lockheed, Northrup Grumann)
- Aerial Pursuit Evasion Games 2003 (transitioned to Boeing UCAV program, demo at Edwards AFB, June 2004)
- Automated Landing transitioned to Northrup Grummann (demo at Edwards AFB, June 2004)
- Sensor Webs (low bandwidth air dropped sensor webs demonstrated at China Lake, Feb 04): now Smart Bird personal UAVs
- Personal back pack sized UAVs (Smart Bird), April 2004-ongoing
- Perch and Move Electric UAV Vehicles, August 2004
- Map Building and Collision Avoidance, November 2004
- Vision Based Landing transitioned to Boeing Frontier, demo first autonomous landing Dec 2005
What’s next for BEAR?

- Fully distributed obstacle avoidance
- Multiple to multiple aerial pursuit evasion
- Swarms of UAVs
- Micro Air Vehicles (Electrics) for indoor operations
- Integration with Sensor Webs of Smart Dust: querying, mobile sensor webs, etc.
- Real time reconfigurable formation flight and aerial refueling
Swarms of UAVs: Personal Aerial Reconnaissance System
NEST Final Experiment:
557 nodes network deployed (Summer 2005)
Closing the Loop in Sensor Networks: Multi-Target Tracking and Pursuit Evasion Games

NEST Final Experiment
August 30, 2005
EECS, UC Berkeley
Micro Robots and Embedded Intelligence

MAST Capability Challenge Showcase
UC Berkeley EECS, Fall 2008
Sam Burden, Andrew Godbehere, Mikhail Lisovich, Hoam Chung, Shankar Sastry
BEAR on the Discovery Channel