Flying Robots and Flying Cars

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My goal for today

- Present two examples for novel Man Machine Interaction
  - **Flying Robots** -- Human Robot Interaction group at MPI Tübingen
  - **Flying Cars** -- European Project (myCopter)
- Both projects show new ways for effective and natural control
- Both integrate humans into the loop in order to build better Human-Machine-Interfaces
The Human: a complex cybernetic system

Our philosophy is to replace the environment with a virtual environment for better experimental control and to decouple the different sensory channels.
Max Planck Institute for Biological Cybernetics
Department of Human Perception, Cognition and Action

Research Groups of the Department

Recognition and Categorization
We can easily and flexibly recognize objects at different levels depending on the task requirements. The goal of the group Recognition and Categorization (RECCAT) is to unravel the mechanisms underlying these two kinds of seemingly effortless tasks that we perform continuously. → [more]

Perception & Action in Virtual Environment
In the Perception & Action in Virtual Environments research group, our aim is to investigate human behavior, perception and cognition using ecologically valid and immersive virtual environments. → [more]

Cybernetics Approach to Perception and Action
In the Cybernetics Approach to Perception and Action research group, our aim is to apply information theory, signal theory and advanced control system methods to understanding self-motion perception and action. → [more]

Human Robot Interaction
The aim of the Human-Robot Interaction group is to study novel ways to interface humans with robots, i.e., autonomous machines that are able to sense the environment, reason about it, and take actions to perform some tasks. → [more]

Cognitive Engineering

Motion Perception in Vehicle Simulation
The aim of the group is to establish a new approach to dynamic simulation. We focus on reproducing the perception of motion, rather than its merely physical characteristics, to increase the simulators performance and the impression of realism. → [more]
Human Robot Interaction group

Bilateral shared control of Flying Robots
Flying Robots: Why

- Visual/Haptic control of a team of flying robots
- “flying eye” suitable for aerial exploration
- "flying hand" suitable for aerial manipulation

- The human commands the collective motion

- The robots must have their autonomy:
  - keep the formation
  - avoid obstacles
  - gather a map of the environment
  - pick and place operation

- The human receives a “suitable” feedback, e.g.:
  - inertia
  - forbidden directions (e.g., obstacles)
  - external disturbances (wind)
A mutually-beneficial interaction between Humans and Robots

Human assistance still mandatory:
- in highly complicated environments (dynamic, unpredictable)
- whenever cognitive processes are needed

Robotic assistance needed to extend the human perception and action abilities
- higher precision and speed
- multi-scale telepresence from microscopy to planetary range
Multi-Robot Mobile Systems: Why

- **Multiple** Robots
  - more effective and robust than a single complex one

- **Mobile** Robots
  - more exploratory than fixed one

- Large number of applications
  - exploration, mapping, surveillance, search and rescue
  - transportation, cooperative manipulation
  - sensor networks
  - mobile infrastructures
  - modular robotics
  - nano-robot medical procedures
Bilateral Shared Control: Why

[Bilhdo, Secchi, Ryll, Bülthoff, RobuffoGiordano, Bilateral Shared Control of Multiple Quadrotors: Balancing autonomy and human assistance with a group of UAVs, IEEE Robotics & Automation Magazine, 2012]
Franchi, Secchi, Ryll, Bülthoff, Robuffo Giordano

Shared Control: Balancing autonomy and human assistance with a group of Quadrotor UAVs,

Robustness and flexibility constitute the main advantages of multiple-robot systems with respect to single-robot ones as per the recent literature. The use of multiple unmanned aerial vehicles (UAVs) combines these benefits with the agility and pervasiveness of aerial platforms [1], [2]. The degree of autonomy of the multi-UAV system should be tuned according to the specificities of the situation under consideration. For regular missions, fully autonomous UAV systems are often appropriate, but, in general, the use of semi-autonomous groups of UAVs, supervised or partially controlled by one or more human operators, is the only viable solution to deal with the complexity and unpredictability of real-world scenarios as, e.g., the case of search and rescue missions or exploration of large/cluttered environments [3]. In addition, the human presence is also mandatory for taking the responsibility of critical decisions in high-risk situations [4].

In this article, we describe a unified framework that allows 1) letting the group of UAVs autonomously control its topology in a safe and stable manner and 2) suitable incorporation of some skilled human operators in the control loop. This way, the human’s superior cognitive capabilities and precise manual skills can be exploited as a valid support for the typical autonomy of a group of UAVs. In fact, drawing
First Goal: Haptic Tele-Navigation

Navigation: the basis for any other (more complex) robotic task (e.g., exploration, mapping, transport, pick and place)

Human (operator) role:
- Gives high-level motion commands (e.g., move one leader, move the centroid, change the formation)
- Elaborates information recorded online by the UAVs
  - visual feedback
  - haptic (force) feedback, i.e., quantitative measurements conveyed by a force

Group of Robots (slave) role:
- Implements the high-level motion commands
- Records environmental measurements to be displayed to the operator
  - plus, autonomously:
    - Avoid obstacles
    - Avoid inter-robot collisions
Main Steps to Achieve Stable Haptic Tele-navigation

- **build a**
  Hardware/Software Platform

- **design and implement a**
  Stable and Tunable Aggregation Control

- **incorporate in the design:**
  High-level Intervention

- **incorporate in the design:**
  Haptic/Visual Telepresence
Main Steps to Achieve Stable Haptic Tele-navigation

- build a Hardware/Software Platform

- design and implement a Stable and Tunable Aggregation Control

- incorporate in the design: High-level Intervention

- incorporate in the design: Haptic/Visual Telepresence
Haptic interfaces
Omega 6 and 3 (3+3-DOF)
- Worksp: 160x110x120 mm
- Maximum force: 12.0 N
- Local force loop: 3 kHz

Custom quadrotor platform
- colored marker
- monocular camera
- brushless controller (BC)
- reflective marker
- microcontroller board (μC board)
- motor
- LiPo Battery
- Q7 board
- modular frame
- Power supply board
Hardware/Software Platform

Robot controller

Inter-robot communication

Sensor data

Force feedback/Sensor data

Human commands

Robot controller
Hardware/Software Platform

Physics (Engine) based Software Simulator

Physical fidelity is tested by comparing the tracking performance of a virtual and real quadrotor flying the same pair of eight-shaped trajectories (a vertical and a horizontal one) The same flight controller gains and parameters, e.g., gains, have been used in the virtual and real case.

The outer loop controls the position and orientation of the quadrotor by reading the robot state (e.g., position and velocity) and providing the appropriate orientation and thrust to the inner loop.

The inner loop acts on the propeller speeds to achieve the desired orientation and thrust provided by the outer loop.

[Lächele et al., SIMPAR 2012]
New Flexible Software Framework for Human/Multi-robot InterHaptivity

[Riedel&Al, subm. to ICRA 2013]

KAIST December 12, 2012 © Heinrich H. Bülthoff
New Flexible Software Framework for Human/Multi-robot InterHaptivity

Haptic device controls the velocity of the formation centroid in the Behavior: **Semi-Autonomous Formation**

Haptic feedback is proportional to the measured velocity error.
Intercontinental Haptic Tele-navigation

[Riedel et al., IAS 2012]

KAIST    December 12, 2012

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Intercontinental Haptic Tele-navigation

2 UAVs are bilaterally teleoperated using an haptic interface passing though an intercontinental communication channel.
Main Steps to Achieve Stable Haptic Tele-navigation

- build a
  Hardware/Software Platform

- design and implement a
  Stable and Tunable
  Aggregation Control

- incorporate in the design:
  High-level
  Intervention

- incorporate in the design:
  Haptic/Visual
  Telepresence
Control of the Group Topology

Flexibility:

- No freedom
- Full freedom

Topology:

- Constant
- Some Property is preserved (e.g., connectivity, rigidity, ...)
- Unconstrained

Examples:
Constant Topology

- local interactions among robots
- a priori fixed geometric formation
- the formation undergoes elastic and reversible transformations
- elasticity: crystal-like behavior (rigid) to a sponge-like one (soft)
Constant Topology: Objectives and Measures

In the constant topology case a **desired shape** is given and must be **maintained**.

**Possible uses:**
- taking precise **measurements**
- achieving **optimal communication**
- transportation

A shape is typically **placement-invariant** and is defined by **constraints**.

**Inter-distances**
- **rotational invariant**
  - time-of-flight sensors, radar sensors
  - stereo cameras

**Relative-bearings**
- **rotational and scale invariant**
  - monocular camera
Constant Topology: Objectives and Measures

Two main approaches:

- measuring **positions**, and constraining **distances**
  
  [Lee et al., *subm. to IEEE/ASME Transaction on Mechatronics*, 2012]
  [Lee et al., ICRA 2011]

- measuring **bearings** (angles), and constraining **bearings**
  
  [Franchi et al., IROS 2011]
Measuring Positions and Constraining Distances

*Multi-UAVs Slave System*

Haptic Teleoperation of Multiple Unmanned Aerial Vehicles over the Internet
Dongjun Lee, Antonio Franchi, Paolo Robuffo Giordano
Hyoung Il Son, Heinrich H. Bülthoff
Measuring Positions and Constraining Distances
Measuring Bearings and Constraining Bearings

High-Level Steering
(e.g., human co-operators using haptic devices)

2D expansion + rotation control
3D translation control

Multi-UAV System

High-level steering: translational motion
The UAVs autonomously keep the bearing formation using onboard vision

Bearing measures obtained from onboard cameras

Modeling and Control of UAV Bearing-Formations with Bilateral High-Level Steering
Antonio Franchi, Carlo Masone, Volker Grabe, Markus Ryll, Heinrich H. Bülthoff, and Paolo Robuffo Giordano
Non-constant Topology while Preserving Some General Property

- **essential-local interactions** among robots (spring-like)
- **undefined and variable** shapes (results of the inter-robot and environment interaction, amoeba-like behavior)
- links can be **broken and restored** but some properties are always preserved
Non-constant Topology while Preserving Some General Property

Two preserved properties:

- communication **connectivity**
  
  [RobuffoGiordano et al., RSS 2011]

- graph **rigidity**
  
  [Zelazo et al., RSS 2012]
Connectivity-constrained Bilateral Shared Control

4 quadrotor UAVs in a cluttered environment

Two humans can guide the group motion with a bilateral shared control architecture
Totally Unconstrained Topology

- **essential-local interactions** among robots (spring-like)
- **undefined** and **variable** shapes
  (results of the inter-robot and environment interaction, amoeba-like behavior)
- links can be **broken** and **restored**
- **challenge**: ensure a stable behavior despite the switching dynamics:
  - use of **passivity theory** and **port-hamiltonian** formalism

[Franchi et al., *IEEE Transaction on Robotics*, 2012]
[Franchi et al., ICRA 2011], [RobuffoGiordano et al., IROS 2011], [Secchi et al., ICRA 2012]
Totally Unconstrained Topology

5 UAVs + 3 UGVs in a cluttered environment

Two humans can guide the group motion with a bilateral shared control architecture
The Next Step:
Beyond a Stable Haptic Tele-navigation
Autonomy from High-rate External Localization (Vicon)

Real world has **no high-rate** position/orientation localization available

Extend the presented algorithms (exploration, connectivity maintenance, ...) taking into account **real world** constraints

- probabilistic sensor model
  - fit the range-visibility model
  - create a different model: modify algorithm

- probabilistic environmental model
  - position uncertainty
  - obstacle uncertainty
Autonomy from External Localization (Vicon)

Improved Hardware Platform
- EKF state estimation
- Automatic calibrations
- Onboard computation capabilities

Vision+IMU estimation
- velocity sensor

[Spica et al., subm. to ICRA 2013] [Grabe et al., ICRA 2012, IROS 2012, subm. to ICRA 2013]
Autonomy with human-in-the-loop

Exploring additional sensor/interaction modalities

- Vestibular
- Tactile
- Stereo vision
- Panoramic vision

Vicon-free Shared Control of multiple UAVs with HIL
Remote control of Unmanned Aerial Vehicles (UAVs)

- Add **vestibular feedback** to enhance situational awareness
  - Scenario: remote teleoperation of a flying vehicle (in our case a quadcopter)
  - Hypothesis: vestibular feedback improves situational awareness for the pilot (and thus facilitates task execution)

Vehicle point of view (visual) + Video stream and motion data ➔ Pilot commands ➔ Vehicle motion (vestibular)
Teleoperation of Unmanned Aerial Vehicles
AHS 66th (2010)
Quick Summary

- Formal framework for establishing a bilateral shared control for interacting with multiple mobile robots

- Fixed topology with deformation
- Property-preserving topology
- Unconstrained Topology

- Global/Local intervention and Telepresence
- Beyond Haptic Tele-Navigation
  - a full multi-sensory experience of flying
  - like a fly
  - using all the tools (toys) in our Cyberneum
What information is needed for a human to pilot a vehicle, either directly or remotely to:

- drive a car, fly an airplane, stabilize a helicopter, etc.

How to present the information in order to:

- increase situational awareness (esp. in remote control tasks)
- facilitate task execution
- develop better/faster training procedures

Multi-sensory Interfaces

- visual cues: tunnel-in-the-sky, glass cockpit
- haptic cues: force-feedback devices
- tactile cues: tactile vests
- vestibular (self-motion) cues
What if we simply fly to work?

myCopter – Enabling Technologies for Personal Aerial Transportation Systems

Prof. Dr. Heinrich H. Bülthoff
Max Planck Institute for Biological Cybernetics
Tübingen, Germany

http://www.mycopter.eu
The dream of flying cars is not new

- Many flying vehicles have been envisioned, but none made it to the market

ConVairAir, 1940s  
Taylor Aerocar, 1950s  
American Historical Society, 1945
Recent developments

- Technology exists to build aircraft for individual transport
  - Many concepts have already been developed

- Drawbacks of current designs
  - Not for everyone (needs a pilot license)
  - Could represent a compromised design
Many challenges ahead

- Our goal is not to design a specific Personal Aerial Vehicle (PAV)
  - “Designing the air vehicle is only a relative small part of overcoming the challenges... The other challenges remain...” [EC, 2007]

We want to address the challenges of building a Personal Aerial Transportation System (PATS)

[EC, 2007] European Commission,
Out of the box - Ideas about the future of air transport, 2007
Rationale for the project

- **Money:** ±100 billion Euros in the EU are lost due to congestion
  - 1% of the EU’s GDP every year [EC, 2007]
- **Fuel:** 6.7 billion gallons of petrol are wasted in traffic jams in USA
  - Each year, 20 times more gasoline than consumed by today’s entire general aviation fleet. [Schrank, 2009]
- **Time:** In Brussels, drivers spend 50 hours a year in road traffic jams.
  - Similar to London, Cologne and Amsterdam [EC, 2011]

**My vision:**
Use the third dimension!

Current transportation systems

Long-distance transportation
+ High-speed (planes / trains)
  – Specific locations (airport / stations)
  – expensive infrastructure (ATC, rails)

Short-distance transportation
+ Door-to-door travel (cars)
  – Relatively slow (traffic jams)
  – expensive infrastructure (roads, bridges, ...)

Existing road traffic has big problems
maintenance costs, peak loads, traffic jams, land usage
Future transportation systems: EU-project myCopter

- Duration: Jan 2011 - Dec 2014
- Project cost: €4,287,529
- Project funding: €3,424,534
Enabling technologies for a short distance commute

Human-Machine Interaction and training issues

Control and navigation of a single PAV

Navigation of multiple PAVs, Swarm-technology

Exploring the socio-technological environment
Novel Human-Machine Interfaces

Make flying as easy as driving

- Multisensory approach: provide additional information with fast and easily understandable cues
  - vision
  - vestibular
  - haptics
  - auditory

- Test Interfaces in simulators
  - MPI CyberMotion Simulator
  - DLR Flying Helicopter Simulator
Novel Human-Machine Interfaces

Novel HMIs are needed for safe and efficient operation of PAVs

- Assess the perceptual and cognitive capabilities of average PAV users
- Evaluations with Highway-in-the-Sky displays
- Support the pilot with haptic cues
Training for “ab-initio” PAV users

Develop training requirements for PAV users

- Develop a model that provides very good handling qualities for easy flying
- Determine the level of training with non-pilots / car drivers
- Investigate emergency situations and the implications for training
A novel approach to control

Develop robust novel algorithms for vision-based control and navigation

Vision-aided localisation and navigation
- Estimate position in dynamic environments
- Build a 3D map for autonomous operation
Vision-aided automatic take-off and landing

No ground based landing guidance, everything on board

- Proper landing place assessment and selection are paramount for safe PAV operations
- Onboard surface reconstruction to recover 3D surface information using a single camera
- Autonomous landing with visual cues

Landing place detection, EPFL CVLab
Decentralised air traffic control

Formation flying along flight corridors
- Global traffic control strategies require swarming behaviour
- Develop flocking algorithms with UAVs
- Evaluations of a Highway-in-the-Sky human-machine interface
Collision avoidance in three dimensions

**Novel sensor technologies for onboard sensing**
- Determine range and bearing of surrounding vehicles
- Active (laser, sonar, radar) vs. passive sensors (vision, acoustic)
- Evaluation with many small flying vehicles
- Light-weight sensor technology for PAVs
Explorations of social and economic impact

The biggest hurdle is acceptance by society
- Safety concerns
- Legal issues
- Ecological aspects
- Noise

Expectations, requirements and challenges
- Structured interviews with experts
- Focus group workshops on a PAV vision and associated requirements
Experimental validation of proposed technologies

Verify selected developed technologies in flight

Flying Helicopter Simulator
- Fly-by-wire / fly-by-light experimental helicopter
- Equipped with many sensors, reconfigurable pilot controls and displays
- Validate HMI concepts and automation technologies
Experimental validation of proposed technologies

Verify selected developed technologies in flight

Flying Helicopter Simulator
- Fly-by-wire / fly-by-light experimental helicopter
- Equipped with many sensors, reconfigurable pilot controls and displays
- Validate HMI concepts and automation technologies
Strategic impacts of a PATS on the longer term

1. Potentially environmental benefits
   - Spending less time and thus energy in traffic
   - Energy efficiency with future engine technologies

2. Use developed technologies for general aviation
   - Automation, navigation, collision avoidance

3. Enhanced flexibility in urban planning
   - Fewer roads, bridges and less maintenance
   - Less conflicts in land usage

Past                                      Present                                      Future

André D Conrad, Wikipedia

Skybum, Wikipedia

Out of the Box, EC 2007

www.famahelicoters.com
My dream PAV

An envisioned Personal Aerial Vehicle, Gareth Padfield, Flight Stability and Control
The enthusiastic myCopter team will help to make my dream come true
Thanks to the rest of my team to keep the lab running while I have a good time at Korea University