H2020 RIA
COMANOID
H2020-RIA-645097

Deliverable D5.2:
Minutes of the consortium meetings
Project acronym: COMANOID
Project full title: Multi-Contact Collaborative Humanoids in Aircraft Manufacturing

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Summary

This document contains minutes of the kick-off meeting for the COMANOID project held on March 4 and March 5 2015 at Airbus’ Saint-Nazaire plant.
Chapter 1
Schedule

1.1  Wednesday 4 March 2015

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<th>Talker</th>
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<tbody>
<tr>
<td>15:00 – 15:30</td>
<td>Reminder of the COMANOID objectives</td>
<td>A. Kheddar</td>
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<tr>
<td>15:30 – 17:00</td>
<td>Visit of Airbus Assembly Site at Saint-Nazaire</td>
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<tr>
<td>17:15 – 17:45</td>
<td>Presentation of Airbus background and discussions</td>
<td>Airbus</td>
</tr>
<tr>
<td>17:45 – 18:45</td>
<td>WP4 Integration, demonstration and benchmarking – Airbus software architecture and detailed planning of work for Year 1</td>
<td>P. Rabaté &amp; A. Suarez-Roos</td>
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1.2  Thursday 5 March 2015

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Talker</th>
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<tbody>
<tr>
<td>09:00 – 09:30</td>
<td>Administrative issues and WP5</td>
<td>A. Kheddar</td>
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<tr>
<td>09:00 – 10:00</td>
<td>Presentation of CNRS background and discussions</td>
<td>A. Kheddar</td>
</tr>
<tr>
<td>10:00 – 10:30</td>
<td>Presentation of DLR background and discussions</td>
<td>C. Ott</td>
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<tr>
<td>11:00 – 11:30</td>
<td>Presentation of Inria background and discussions</td>
<td>P.-B. Wieber &amp; F. Chaumette</td>
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<tr>
<td>11:30 – 12:00</td>
<td>Presentation of UniRoma background and discussions</td>
<td>G. Oriolo</td>
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<tr>
<td>13:30 – 14:00</td>
<td>WP1: Multi-contact planning and control â¬Å, detailed planning of work for Year 1</td>
<td>C. Ott</td>
</tr>
<tr>
<td>14:00 – 14:30</td>
<td>WP2: Perception and localization â¬Å, detailed planning of work for Year 1</td>
<td>F. Chaumette</td>
</tr>
<tr>
<td>14:30 – 15:00</td>
<td>WP3: Safety for human and humanoids coworkers â¬Å, detailed planning of work for Year 1</td>
<td>G. Oriolo</td>
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Chapter 2
Minutes

In the scheduled order.

2.1 General presentation (A. Kheddar)

2.1.1 Project presentation
- Highly regarded project by the EU (very targeted and focused project with important contribution/impact)
- Experiments on real factory environment? (3 levels of "simulation")
- Co-existence not cooperation
- Humanoids in 2025? (date) Waiting for manufactured humanoid robots

2.1.2 Work in progress – ToDos
- Web site in progress
- Logo
- Money dispatch (contact Laurent Renouf @ CNRS)

2.1.3 Management issues
- Consortium agreement signed by all
- Communication infrastructure (one ml for PI, one ml for EB, one ml for all)
- Gender action plan
- Don’t forget the project in your papers’ acknowledgment
- D4.1 (@M6) Demonstrator specification report [Airbus] (already defined in the proposal).
  **Issue of data confidentiality w.r.t. Airbus data**
2.1.4 Miscellaneous

- Software architecture
- Link with FP7 on-going projects (KOROIBOT/WALKMAN/SAPHARI)
- Target TRL: 6 (for Airbus: high-expectation, hand-over to industrials, 7/8 in “standard” TRL levels) (already some discussion with potential humanoid manufacturers (Honda, Google, Kawada…)). **This is not Airbus TRL but technology TRL.**

2.2 WP4 presentation (Airbus)

2.2.1 Airbus activity

- Low production rate
- Very high quality requirements (\(1\text{ mm, }0.5\text{Å}\))
- Very qualified workers

Benefits of humanoids: to go where mobile manipulator cannot go.

2.2.2 Tasks

T4.1: Demonstrator specifications (M6)

T4.2: Software integration and development policy (M36)

T4.3: On-site experiments (M47)

T4.4: Requirements and recommendations for the use of humanoids (M48)

Everybody is involved in this WP, integration stars now!

2.2.3 Scenario specification

(i) Overall scenario

(ii) Description of the environment

(iii) CAD model of parts and tooling (within what is possible)

(iv) Description of printing process and requirements

The scenario described in the proposal is close to the final one but will be refined after discussion with the floor guys and remarks from the partners.

Common description of the high-level of the demonstration (mission description should be written once for all robots)

Details of the content of the description have to be discussed but specifications should be “relaxed” w.r.t. to execution of the tasks (e.g. contact points should not be specified but forbidden contacts have to be)
Some developments can be ported to the COBOT platform (e.g. perception is not specific to humanoids)

T4.3: TRL 6 (European)
T4.4: end of the project but we should think about it from now

2.3 Background – CNRS

2.3.1 3 teams

LIRMM/IDH and JRL(A. Kheddar)
Multi-contact planning/control
Falling strategies (1 PhD student, experiments starting soon, expecting preliminary results before end of Y1)
Alternative touch sensing/flexible covers (good for safety/falling)
Demonstrator with HRP-4

I3S (A. Comport)
Localization and map generation (robustness in presence of humans)
SLAM for walking and MCP
Matching with objects from DMU (coordinated effort with INRIA and Airbus IG)

2.3.2 MCP

• Already achieved a lot in LIRMM/JRL
• New HRP-2 on the way (after DARPA challenge) shall improve the robot’s capabilities (especially grasp wise)
• Same framework allows force control

2.3.3 Walking
Integration of Pierre-Brice Wieber’s latest PG on HRP-4.

2.3.4 Extension

• Task driven MCP
• Skill/application-driven MCP
• SLAM-based MCP

2.3.5 SLAM

• Integrated to ROS
• DARPA challenge (remote visualization of valve and car mapping)
• SLAM cannot solve everything (e.g. inside the vehicle, the robot cannot see the pedals)
2.3.6 Questions

- How to manage gap between the reality and the model?
- The automaton deals with uncertainty already (w.r.t. environment) and the SLAM detects outliers (humans/change compared to the model) but what to do with this information is outside the scope of the project although we can capitalize on what COBOT is doing.

2.4 Background – DLR

- Torque controlled humanoid robot (TORO): experimental platform not a product
- Multi-contact control (T1.3)
- Bipedal walking/MCP
- Visual-servoing/Contact estimation/Safety

2.4.1 MC control

Multi-task control
Only used on the upper body until now

Force distribution in legged robots
Floating mobile platform for balancing

2.4.2 Bipedal walking

Capture point already used on TORO
Extension to 3D walking (Divergent Component of Motion (Takenaka))
Works well in simulation, hopefully ported to the real robot within the project

2.4.3 Multi-contact planning

Based on capability map

2.4.4 Contact estimation

Integrate results from the SAPHARI project

2.4.5 Goals

1. Extension of the balancing controller
2. Interface to motion planning for multi-contact situations
3. Force-based walking using DCM
4. Integration of advanced skills (VS/Safety)
5. Use case
2.5 Background – INRIA

2.5.1 LAGADIC
- Visual servoing
- Visual tracking

Applied to vision-based navigation/manipulation
Many platforms in the lab (only one humanoid: ROMEO) and through collaborations
3D localization with numerous applications
Template matching with mutual information
Direct visual servoing (very accurate)
Experience with humanoid robots (HRP-2, REEM, ROMEO)
Autonomous navigation
ViSP

2.5.2 BIPOP

Only bipedal walking
No robot but applied to a lot of robots through collaborations (not yet in DLR)
Reactive behaviors important for safety (already working in simulation, moving to the real robots within COMANOID)
Falls will happen
- We can assess that the robot is going to fall
- Which strategy to adopt when it is going to adapt? Multiple goals (take contacts when/if necessary)

2.6 Background – UNIROMA

Related European projects
- SAPHARI
- SYMPLEXITY

WP3: safety of humans, of the humanoid, of the environment
Safety/Motion planning/Humanoids
Safety, coexistence, interaction/collaboration

2.6.1 Collision avoidance
Collision detection and reaction
Coexistence and intentional contacts
Classification of contacts based on the analysis of residuals
2.6.2 Motion planning
Task-constrained motion planning
Applied to whole-body motion planning
- Use a catalog of precomputed CoM paths as primitives
- The planner automatically switches between different walking gait

2.6.3 Visual navigation in an office environment using simple features
Odometry localization
Gait generation (zmp/com generation)
Manual guidance (interaction based on perceived perturbation of the equilibrium)

2.7 Work plan – WP1
Main deliverables at M36 (most work should be done by then)
Objectives:
1. Develop core technology in MCP and control
2. Robust walking
3. Visual servoing
Split into 4 tasks (3@M1, VS@M12)

2.7.1 MCP Y1 objectives
- Planning quasi-static motions for m-c tasks
- Use representative models from Airbus

2.7.2 Visual servoing Y1 objectives
Start in M12

2.7.3 Balancing and multi-contact control Y1 objectives
MC balancing using predefined contact points
Establish and release contacts statically
Prepare MC balancer for combination with planning (Integration start)

2.7.4 Robust walking and standing Y1 objectives
First version of torque based walking implemented on TORO (DLR) (simulation at least)
Experiments on HRP-4: climbing stairs (CNRS/INRIA)
Initial guidelines for safe walking (UNIROMA1)
2.7.5 Miscellaneous
Simulator? Which one should be adopted by the consortium?

2.8 Work plan – WP2

T2.1: Localization and map generation (I3S)
T2.2: Object recognition (I3S)
T2.3: Visual tracking (LAGADIC)
T2.4: Contact sensing (UNIROMA1)

2.8.1 M2.1@M12
First version of DSLAM and object recognition provided with appropriate interfaces for DMU updates (T2.1/T2.2) (should be easy)

2.8.2 T2.2
Off-line objects learning with RGB-D
On-line object recognition and localization

2.8.3 T2.3
Alternative to RGB-D and 3D localization: focus on particular parts.
Y1: start implementation for demonstration on the COBOT platform.

2.8.4 T2.4
Virtual force sensor (DLR/UNIROMA1) based on results from SAPHARI
SynTouch solution (CNRS - LIRMM)
Y1: this task starts @ M6.

2.8.5 Which sensors?
What we have for now, change if needed or new sensors appear on the market.

2.9 Work plan – WP3

2.9.1 Objective
Safety of humans, of the humanoid and the environment
2.9.2 COMANOID vs. SAPHARI

- Humanoids vs. manipulators
- Humans in the workspace but no physical interaction (easier)
- Complex environment
- On-board sensors

2.9.3 T3.1

Human-humanoid safe coexistence and physical interaction

**Detection** Need for gazing strategies

**Avoidance** Need for balance maintenance

**Reaction** Need contact sensing

**Collaboration** Outside of the demo scenario

2.9.4 T3.2

Human safety issues in planning and control
Should be introduced as constraints in the planner

2.9.5 T3.3

Safe falls of humanoid robots
INRIA

2.9.6 T3.4

Humanoid safety procedure and assessment in operation sites
Should include realistic rules from current procedures in Airbus

2.9.7 Questions/Remarks

**Triggering security system through alarms**

- Vision-based alarms
- Contact-based alarms

The alarm should be informative (direction, speed...)

**Collision avoidance**

Can use stepping or new contacts
Safety layer objective?
Stop safely or locally deform the plans until the situation is defused

Robust alarms are critical
- Difficult for vision
- Easier for contact (e.g. contact area)

Why embedded sensors only?
Business constraint (time spent equipping the inside of the aircraft is wasted time)

Year 1 focus?
T3.1 (collision avoidance and reaction to collisions)
Chapter 3

Slides

In the order they were shown at the meeting.

3.1 Kick-off meeting – Introduction

COMANOID

H2020 RIA Project

Schedule 4 march

<table>
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<tr>
<th>Time</th>
<th>Activity</th>
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<tr>
<td>15:00 – 15:30</td>
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<td>17:15 – 18:45</td>
<td>Presentation of Airbus background and discussions – Weber</td>
</tr>
<tr>
<td>18:45 – 19:15</td>
<td>IPA7 Integration, demonstration and benchmarking – Airbus software architecture and detailed planning for Year 1 – Robbi – Suarez Roca</td>
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Wednesday 4 March 2015

Schedule 5 march

<table>
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<td>Administrative issues and WPs – Khodiar</td>
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<td>9:30 – 10:30</td>
<td>Presentation of CNRIs background and discussions – Khodiar</td>
</tr>
<tr>
<td>10:30 – 10:50</td>
<td>Presentation of COMANOID background and discussions – Weber</td>
</tr>
<tr>
<td>11:00 – 12:00</td>
<td>Presentation of 6th background and discussions – Chaumette – Weber</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>Presentation of 5th background and discussions – Osiana</td>
</tr>
<tr>
<td>13:00 – 14:30</td>
<td>WP1. MCI: context planning and control – detailed planning of work for Year 1 – Osima</td>
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<tr>
<td>14:00 – 14:30</td>
<td>Presentation of COMANOID to David Lyons (Head of Airbus Saint-Nazaire Plant) – Parisi</td>
</tr>
<tr>
<td>14:30 – 15:00</td>
<td>WP2. Perception and localization – detailed planning of work for Year 1 – Chaumette</td>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>WP5. Safety for human and robotic coexistence – detailed planning of work for Year 1 – Osima</td>
</tr>
<tr>
<td>16:00 – 16:30</td>
<td>Coffee Break and Final discussions</td>
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Information on the Call

- Type of funding scheme
  - Research and Innovation Actions
- Topic
  - ICT-23-2014 Robotics
- Main pillar
  - Industrial Leadership
Airbus Group needs (in brief)

- Robotics in aircraft manufacturing
- Human working operations divided in two categories
  - High added-value tasks
  - None added-value tasks (to be done by robots)
    • Dangerous for human workers
    • Health risks
    • Agreed by trade union and cartel
    • Require high precision less dexterity

Airbus Experience with Cobots

Floor shops in practice

Other floor shops

Airbus Group interest

- As can be seen from floor shops
  - Mobile robots cannot access Cargo and other areas
  - Railed-ported robotic arms not possible
  - Robot must work inside product
  - Not like in car company
  - To go from one level to the other
    • Use of stairs/ladders
- Constraint
  - Share workspace with human workers
  - Share same tools with human workers

Summary of COMANOID objectives

- Deploy humanoids for non-added value tasks identified by Airbus Group in civilian airliner assembly operations
- Precise accessibility through robust walking, whole body multi-contact planning motion with advanced embedded 3D dense SLAM localization and visuo-force servoing capabilities under safety requirements in the presence of human coworkers
- Demonstration use-case
  - Scale 1:1 airplane
- Showcase
  - Real aircraft use-cases with two humanoid robots: the HRP-4 and TORO

Partners

- CNRS
  - Labs: JRL + LIRMM-IDH (Kheddar), I3S (Comport) + third parties: AIST (Kenehiro), Univ. Mtp, Univ. Nice
- DLR
  - Robotic systems department (Ott)
- INRIA
  - Teams: Lagadig (Chaumette), Bipop (Wieber)
- UNIROMA1
  - DIAG (Oriolo)
- Airbus Group
  - AGI (Rabaté, Suarez)

Known environment full CAD
Schematic plan (roadmap)

Urgent todos

• Website
  — www.comanoid.cnrs.fr
  — Domains comanoid.eu comanoid.org... will be bought

• Logo
  — To be done

• Money transfer
  — Contact CNRS: Laurent Renouf

Management issues

• D5.1@M1
  — Consortium Agreement signed by all partners

• D5.2@M2
  — Setup of the communication infrastructure (web-server, mailing list, net-meeting, etc.)
  — Website
    • www.comanoid.cnrs.fr
  — Domains comanoid.eu comanoid.org... will be bought

• D5.3@M1
  — Minutes of the Milestone review consortium meetings

• D5.5@M3
  — Gender action plan

• D5.6@M6
  — Exploitation and Dissemination Plan including Data Management Plan (DMP)

This meeting discussion

• Deliverable to come
  — D4.1@M6 (30 June 2015): Demonstrator specification report [Airbus]

• Software architecture

• Y1 targets in each WP/tasks

Conclusion

• Very targeted and focus project
  — brings humanoid robots to manufacturing humanoids

• Link with FP7 on-going projects
  — KOROIBOT
  — WALKMAN
  — SAPHARI
  — …

• Targeted TRL for key technologies: 6

• Visit of Airbus
3.2 Background – Airbus
Localization and Mapping

SLAM
- Scan the environment
- Use a transponder objects
- Collect data
- Localize with respect to known objects
- Add new detected objects

Probabilistic model manage uncertainty while incrementing knowledge
Several SLAM algorithms within ROS
- Additional sensors to classify and share data
3.3 Work plan – WP4

Motivations for Humanoids

Go where no mobile manipulator can go

WP4

Tasks

- Task 4.1: Demonstration specification
- Task 4.2: Software integration and development policy
- Task 4.3: On-site experiment and evaluation
- Task 4.4: Requirements and recommendations

Deliverables and marks of delivery

- D4.1: Demonstration specification report (WP4.1)
- D4.2: Integration/humanoid robot software and Airbus III interface specification (WP4.2)
- D4.3: Final demonstration and technology recommendations (WP4.3)
- D4.4: Final presentation in front of Airbus Group review panel (WP4.4)

Workshops

- WP4.1: Scenario specification and mastering architecture issues (WP4.1)
- WP4.2: Software policy agreed and shared responsibilities put in place (WP4.2)
- WP4.3: Final benchmark software (WP4.3)
- WP4.4: Final demonstration achieved (WP4.4)
- WP4.5: Final presentation (WP4.5)
Task 4.1 Demonstration specifications

AIRCRAFT (4.4, 4.5)

Demonstrator specification accepted by all partners

AIRCRAFT will deliver the three main demonstrators that will punctuate the project in terms of technology readiness level (TRL) for the four demonstrators:

- TRL 6 achievement
- TRL 4.5 achievement

AIRCRAFT will report the demonstration environment in order to make sure that the main demonstrator isolation below with respect to the demonstration results of Task 4.1: The demonstration environment could also be adapted to ensure that the demonstrator isolation is maintained.

AIRCRAFT will provide the four demonstrators that will be used for the demonstration activities in order to ensure that the demonstrator isolation is maintained.

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AIRCRAFT will deliver the four demons...
3.4 Background – CNRS

CNRS contribution

• Three groups
  • LIRMM-IDH and JRL
    – Multi-contact planning and control
    – Falling strategies
    – Alternative touch sensing/flexible covers
    – Demonstrator with HRP-4 humanoid robot
  • I3S
    – Localization and map generation
      • Robustness in presence of human and repetitive pattern
    – SLAM for walking and MCP
    – Matching with objects from DMU and DMU

Multi-contact planning

• Principle
  – Allow contact to occur on whole humanoid body
  – Use all the surrounding environment to contact for motion or task

Multi-contact planning control (SoA)

QP MPC control

Walking (Integration with Inria PBW)
Extension

- Task-driven multi-contact planning
- Skill/application-driven MPC
- SLAM-based MPC

SLAM

- Ros integration
  - DARPA challenge (remote visualization of valve and car mapping)

SLAM Ladder

SLAM vehicle

SLAM Vehicle

Conclusion

- Work started
  - we will capitalize on the DARPA experiment
- Get DMU from Airbus and first simulation of MCP
- Start with Inria (Chaumette) for VS
- MCP Planning with TORO (Ott)
3.5 Background – DLR

DLR Background related to COMANOID

Christian Ott
German Aerospace Center (DLR)

DLR’s role in COMANOID

1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
3) Large contribution to
   • bipedal walking (T1.4, 12PM)
   • multi-contact planning (T1.1, 12PM)
4) Small contribution to
   • visual servoing (T1.2, 6PM)
   • contact estimation (T2.4, 9PM)
   • safety (T3.3, 6PM)

Torque Controlled Robots @ DLR

Advantages of Torque Sensing

Light-weight robots with elastic joints
Joint torque sensor
Safe human-robot interaction
Compliance control
Disturbance Observer
Identification
Movement accuracy
Active vibration damping
Safe human-robot interaction
Light-weight robots with elastic joints
Joint torque sensor
Safe human-robot interaction
Compliance control
Disturbance Observer
Identification
Movement accuracy
Active vibration damping
Advantages of Torque Sensing

- Light weight robot with elastic joints
- Joint torque sensing
- Motor
- Elasticity
- Segment

Movement

Safe human-robot-interaction

Joint torque sensing & control

Humanoid robot TORO

- Joint torque sensing & control
- Small foot size: 19 x 9.5 cm
- IMU in head & trunk
- FTS in foot for position based control
- Sensorized head (stereo vision & Kinect)
- Simple prosthetic hands (iLIMB)

Compliant Manipulation

[Ott & Albu-Schäffer, TRO 2008]

Robustness: Passive Based Control

Performance: Joint Torque Feedback (noncollocated)

Humanoid robot TORO

- Height: 1.74 m
- Mass: 76.4 kg
- Battery duration approx. 1 hour
- 25 joints can be operated in position and torque controlled mode (legs, arms, wrists)
- Joints are based on the DLR-Kuka LightWeight-Arm III
- 3 joints are operated in position controlled mode (neck)
- Prosthetic hands with 12 DoF in total
Hierarchical Nullspaces

\[ J(q) = \begin{bmatrix} J_1 & J_2 & \cdots & J_n \end{bmatrix} \]

1) Decoupled inertia (dyn. consistency)
2) Hierarchy/prioritization
3) Minimal dimension to fulfill the task

Multi-Task Control

Multi-Task Control

Multi-Task Control
Hierarchical Nullspaces

Hierarchical nullspace velocity coordinates

Controller Design

Closed Loop Dynamics

Simulations

DLR’s role in COMANOID

1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
   a) Multi-contact control
3) Large contribution to
   a) bipedal walking (T1.1, 12PM)
   b) multi-contact prehension (T1.1, 12PM)
4) Small contribution to
   a) visual tracking (T1.2, 14PM)
   b) contact estimation (T1.4, 12PM)
   c) safety (T1.3, 24PM)
Balancing & Posture Control
Compliant COM control [Hyon & Cheng, 2006]
\[ \mathbf{F}_{\text{COM}} = M(q) - K_v(q - q_d) - K_q(q - q_d) \]

Trunk orientation control
\[ T_{\text{COM}} = \begin{bmatrix} \text{Feedback} \end{bmatrix} \begin{bmatrix} \text{Ext} \end{bmatrix} \]

Contact force control via joint torques

Grasping & Balancing

Force distribution
Relation between balancing wrench & contact forces

Constraints:
- Unilateral contact: \( f_i > 0 \) (implicit handling of ZMP constraints)
- Friction cone constraints

Contact force control via joint torques
Multibody robot model
\[ M(q) \]
1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
   a) Multi-task control
   b) Force distribution in legged robots
3) Large contribution to
   • bipedal walking (T1.4, 12PM)
   • multi-contact planning (T1.1, 12PM)
4) Small contribution to
   • visual servoing (T1.2, 6PM)
   • contact estimation (T2.4, 9PM)
   • safety (T3.3, 6PM)

DLR's role in COMANOID

Walking Stabilization

Capture Point Control

Extension to 3D walking
Enhanced Centroidal Momentum Pivot point (eCMP).

DCM Tracking Control

Point mass simulation

Capability map

Integrated grasp and motion planning

DLR’s role in COMANOID

1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
   a) Multi-task control
   b) Force distribution in legged robots
3) Large contribution to
   • bipedal walking (T1.4, 12PM)
   • multi-contact planning (T1.1, 12PM)
4) Small contribution to
   • visual servoing (T1.2, 6PM)
   • contact estimation (T2.4, 9PM)
   • safety (T3.3, 6PM)
DLR’s role in COMANOID

1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
   a) Multi-task control
   b) Force distribution in legged robots
3) Large contribution to
   - Speed control (T1.4, 12PM)
   - Multi-contact planning (T1.1, 12PM)
4) Small contribution to
   - Visual servoing (T1.2, 8PM)
   - Contact estimation (T2.4, 8PM)
   - Safety (T2.3, 8PM)

Kinesthetic Teaching for Humans

Interaction aware balancing (1)

Interaction aware balancing (2)

Interaction aware balancing (3)

Observational Teaching

Intuitive Programming

Observational Demonstration

Kinesthetic Demonstration

Teaching at the body surface

Virtual teaching at specific locations

Robot Model (R: ZMP)

Implementation of this observer requires
- Measurement of base link orientation
- Base link velocity and angular velocity

\[ \dot{x} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \dot{z} \end{bmatrix} + \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} + \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \end{bmatrix} \]

Cost function for model predictive control:

\[ J = \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \end{bmatrix}^T \begin{bmatrix} P_0 & P_1 & P_2 \\ P_1 & P_3 & P_4 \\ P_2 & P_4 & P_5 \end{bmatrix} \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \end{bmatrix} + \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \end{bmatrix}^T \begin{bmatrix} Q_0 & Q_1 & Q_2 \\ Q_1 & Q_3 & Q_4 \\ Q_2 & Q_4 & Q_5 \end{bmatrix} \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \end{bmatrix} \]
Evaluation of the balancer:
Predefined motion of the arms (under compliant control) for pushing against a table.

Balancing experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Pushing against table with external force</td>
</tr>
<tr>
<td>B</td>
<td>Pushing against table without external force</td>
</tr>
</tbody>
</table>

With external force
Without external force

DLR’s role in COMANOID

1) Torque controlled humanoid robot TORO
2) Develop algorithms for multi-contact control (T1.3, 24PM)
   a) Multi-task control
   b) Force distribution in legged robots
3) Large contribution to
   a) Bipedal walking (T1.4, 12PM)
   b) Multi-contact planning (T1.1, 12PM)
4) Small contribution to
   a) Visual servoing (T2.2, 6PM)
   b) Safety (T2.3, 6PM)

A Selection of specific Contributions & Expectations in COMANOID

1) Extension of the balancing controller
   a) Tracking formulation
   b) Combination with multi-task control framework
2) Interface to motion planning for multi-contact situations
   a) Using ideas from robot grasping for contact planning
3) Force-based walking using the DCM concept
4) Integration of advance skills
   a) Visual servoing
   b) Safety
5) USE CASE!

Thank you very much for your kind attention!
3.6 Background – INRIA

3.6.1 Background – Lagadic

Lagadic:
visual servoing in robotics,
computer vision and augmented reality
François Chaumette

Inria Rennes Bretagne Atlantique & Irisa from Dec. 2004
& Inria Sophia-Antipolis from April 2012

http://team.inria.fr/lagadic

Implication in Comanoid
Involved in
• WP1 -> T1.2: visual servoing (18 + 3 MM)
• WP2 -> T2.3: visual tracking (18 + 2 MM)
• WP4: integration/demonstration (6 + 1 MM)
• WP5 (0 + 2 MM)

The group
Currently 32 scientists: 27 in Rennes, 5 in Sophia-Antipolis
• Permanent staff: 8
• 18 Ph.D. students
• 2 post-doc
• 4 temporary engineers

Scientific objectives
To develop generic methods in
• real time visual tracking
• visual servoing
• control
that we want to apply for:
• vision-based manipulation
• vision-based navigation
• medical robotics

Other application:
• augmented reality

Experimental platforms
Experimental validation, tests before transfer, demonstrations
Collaborations with partners for other platforms (μ-robot, outdoors UAVs)
Main recent contributions

1. Visual tracking
   - A necessary input for visual servoing (usually)
   - Also useful in computer vision and augmented reality
2. Visual servoing and control

3D localization by model-based tracking
Numerous applications and improvements

Main recent contributions

1. Visual tracking
2. Visual servoing and control

Template tracking using mutual information

- MI is far more robust than SSD in case of illumination changes
- MI has a convergence domain as wide as ESM

Multi-modal images can be considered

- Infrared versus airborne template

Direct visual servoing

Goal: Using directly the intensity level of all pixels as input of visual servoing

Advantages:
- No image processing: neither features tracking nor matching,
- Excellent positioning accuracy

Drawbacks:
- Small convergence domain for 6 dof due to high non-linearities
- Approach sensitive to illumination changes
- Maximizing mutual information:
- Ensure robustness to illumination changes
- Allows multi-modal visual servoing (specification vs execution)

Direct VS from depth map

Motion compensation by US visual servoing

Goal: soft-tissue motion compensation during ultrasound imaging

- US intensity-based VS with desired image = initial image
- Constant image 3D gradient estimated at initial position
- Repetitive predictive controller (R-GPC) to reject periodic disturbance

Humanoid robotics

Romeo grasping demo
using wrist-servoing control
Autonomous navigation with obstacles avoidance

- Visual navigation from a visual memory (no SLAM)
- Control expressed as visual features to be seen (IBVS)
- Using a laser-range finder for obstacles localization
- Using a pan-tilt camera to observe the visual path while avoiding obstacles
- Redundancy framework to combine visual navigation and obstacles avoidance

Complementary approach developed in Sophia Antipolis:
- Dense SLAM with spherical views

Software development: ViSP (GNU GPL v2)

Int. collaborations & current fundings

- ACRV: P. Corke (Univ. Queensland), R. Mahony (ANU)
- Medical robotics: N. Navab (TUM), P. Dupont (Boston Children Hospital)
- Augmented reality: H. Uchiyama (Kyushu Univ.)
- Vision-based manipulation:
  - ARI P2N Nanorobots (grant Ferram): 2011-2015
  - MEST Nanorobots (grant Birmingham): 2015-2018
- Vision-based navigation:
  - Dense SLAM (grant Lagadig) 2013-2015
- Aerial vehicles:
  - SAV (grant Prime: Astrium) 2011-2015
  - ARI VISPOL (grant Divinec) 2013-2016
  - ESA IRESIS (grant: Commission of the European Communities) 2014-2016
  - ARI VISPOL (grant: Divinec) 2016-2017
- Robotics & automation:
  - ARI VISPOL (grant: Divinec) 2016-2017
- Humanoid robotics:
  - Espace Robotics (grant: CNRS): 2011-2017
  - Dense SLAM (grant: Achievement Robotics): 2013-2016
  - ARI VISPOL (grant: Divinec) 2016-2017

Support for the development of the ViSP C++ library, but also internally (eg. for SLAM and MBT).
3.6.2 Background – BiPoP

Biped Walking in COMANOID
Pierre-Brice Wieber
INRIA Grenoble Rhône-Alpes

In Aldebaran’s robots

In JRL’s robot

In DLR’s robot, during COMANOID?

Reactive, online motion generation

Gracefully tackles conflicting goals
**Reaching a target, if possible**

**Walking, if necessary**

Walking towards a moving target.

**Up and downstairs**

**ec.europa.eu/research**

- **TRL 3 — experimental proof of concept**
  This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.

- **TRL 6 — technology demonstrated in relevant environment**
  The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated operational environment.

**Harder will be the fall**

**Monitor capturability to assess balance safety**

**Using hand support, if necessary**
3.7 Background – UNIROMA

UNIROMA1: background

Dipartimento di Ingegneria Informatica, Automatica e Gestionale

recent EU-funded projects

- FP6-FP7
  - CyberWalk: The CyberCarpet: Enabling Omni-directional Walking in Virtual Worlds (05-08)
  - PHRIENDS: Physical Human-Robot Interaction: Dependability and Safety (06-09)
  - SaPhARI: Safe and Autonomous Physical Human-Aware Robot Interaction (11-15)

- in H2020
  - SYMPLEXITY: Symbiotic Human-Robot Solutions for Complex Surface Finishing Operations (15-18)

research group

- Robotics Lab at DIAG, Sapienza University of Rome
- permanent staff
  - Alessandro De Luca, Leonardo Lavini, Giuseppe Oriolo, Marilena Vendittelli
- 2 post-docs
  - Massimo Cefalo, Fabrizio Flacco
- 6 PhD students
- contacts
  - e-mail: {lastname}@diag.uniroma1.it
  - web: www.diag.uniroma1.it/~labrob
  - youtube: www.youtube.com/user/RoboticsLabSapienza

UNIROMA1 responsibilities

- WP3 leader (46 pm)
- T1.2: Visual servoing for planning and multi-contact (10)
- T1.4: Robust walking and standing (16)
- T2.1: Contact sensing (18)
- WP4 (18)
- WP5 (3)

UNIROMA1 in detail

<table>
<thead>
<tr>
<th>Work package number</th>
<th>Start date or starting event</th>
<th>WP</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP2</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>WP3</td>
<td>Safety for human and humanoid coordination</td>
<td>2</td>
</tr>
<tr>
<td>WP4</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

 objective: safety of humans, of the humanoid, of the environment

- T3.1: Human-humanoid safe coexistence and physical interaction
- T3.2: Human safety issues in planning and control
- T3.3: Safe falls of humanoid robots
- T3.4: Humanoid safety procedures and assessment in operation sites

relevant background

- research on safety, coexistence, interaction
- research on motion planning
- research on humanoids
**safety, coexistence, interaction**

- collision avoidance
- collision detection
- collision reaction
- detection of intentional contact

**collision detection and reaction**

- model-based residual method for collision detection using joint sensors (position, torque) and no exteroceptive sensors
- detection time: 2-3 ms; reaction time 1-2 ms
- different strategies for reaction

**estimation of contact forces**

- objective: detect, localize, classify contact → estimate force
- uses depth camera, joint sensors

**task-constrained motion planning (TCMP)**

- randomized planner with control-based motion generation
- assigned task path (trajectory, set-point) is guaranteed
- all other constraints (kinematic, dynamic) satisfied
- exploration vs exploitation trade-off

**coexistence and intentional contacts**

- safe human-robot coexistence
- simple gestures for establishing intentional contacts when collaboration is desired

**motion planning**

- task-constrained motion planning (TCMP)
- TCMP extensions: cyclicity, moving obstacles
- whole-body motion planning for humanoids

**collision avoidance**

- distance estimation using depth camera
- computation directly in depth space
- potential-based avoidance at the EE and link levels

**TCMP: cyclicity, moving obstacles**
whole-body motion planning (WBMP)
- use a catalog of precomputed CoM motion primitives as seeds for motion generation; e.g.,
  - stepping
  - climbing
  - squatting
  - jumping

WBMP: results
- stepping motions are automatically generated by the planner
- task-driven gait changes automatically generated by the planner
- scene-driven gait change automatically generated by the planner

humanoids
- visual navigation
- odometric localization
- gait generation
- manual guidance

odometric localization
- kinematic EKF with head pose measurements via V-SLAM
- uses camera, IMU, joint encoders, foot sensors

visual navigation
- walking in office-like environments
- purely vision-based

gait generation
- generation of CoM bounded trajectories for a given ZMP trajectory
- anticipative behavior which naturally exploits the ZMP-CoM relationship
- design extension: simultaneously solve for the ZMP & CoM trajectory in order to achieve a given path
- analytical solution
**manual guidance**

- simple scheme **not** based on force sensors
- interaction **based** on perceived perturbation of the equilibrium
- uses the capture point/divergent component of motion of the stabilised humanoid as **sensing device**
- interaction not limited to hands
3.8 Work plan – WP1

WP1: Multi-contact planning and control
Christian Ott

Objectives

1. Develop core technology in multi-contact planning and control for humanoids to move and work in highly uneven areas such as cargo space
2. Robust walking when support other than floor is available
3. Visual servoing components for various contact operations, visual servoing in walking

Deliverables

Milestones
1. M1.1 @ M18: Demonstration of robust balancing utilizing predefined contact points [DLR, CNRS]
2. M1.2 @ M24: Multi-contact planner based on models updated from SLAM [CNRS, AIRBUS]
3. M1.3 @ M30: Visual servoing integrated in multi-contact control, walking and posture reaching contact [INRIA, CNRS, DLR]
4. M1.4 @ M30: Multi-contact planner and control, walking using safety recommendations [INRIA, AIRBUS]

Deliverables
1. D1.1 @ M36: Report on multi-contact planning and control [DLR]
2. D1.2 @ M36: Report on walking control [INRIA]

No milestones or deliverables in Y1.

T1.1: Multi-contact planning CNRS (25), DLR (12PM), AIRBUS (12)

Success: The humanoids HRP-4 and TORO are capable of finding appropriate contact sequences to move from a start location to an end location. The humanoids are also capable to take an appropriate posture prior to task execution and adjust it on-line.

Y1 goal: • CNRS & DLR: Planning quasi-static motions for multi-contact tasks (for TORO & HRP4)
• Using representative models from AIRBUS
• First version of planner working on AIRBUS CAD data

T1.2: Visual servoing for walking and multi-contact INRIA (21), UNIROMA1 (10), DLR (6), CNRS (4)

Success: The humanoid robots are capable of establishing and opening contacts using vision and force sensing. In a multi-contact configuration, the humanoid robot is capable of reaching visual pose or tracking an object while sustaining contacts.

Y1 goal: • CNRS & DLR: Planning quasi-static motions for multi-contact tasks (for TORO & HRP4)
• Using representative models from AIRBUS

T1.3: Balancing and multi-contact control CNRS (25), DLR (12PM), AIRBUS (12)

Success: Robust and stable multi-contact motions accounting for constraints and integrating vision together with safety constraints.

Y1 goal: • MC balancing using predefined contact points
• Be able to establish and release contacts statically
• Start integration: prepare MC balancer for combination with planning

T1.4: Robust walking and standing INRIA (21), UNIROMA1 (10), AIRBUS (12)

Schedule: M1 – M42
main deliverables @ M36

Effort: 194 PM
• DLR: 54 PM
• INRIA: 54 PM
• CNRS: 48 PM
• UNIROMA1: 26 PM
• AIRBUS: 12 PM

WP Overview

Description of Work

M1 – M42

T 1.1: Multi-contact planning
CNRS (25), DLR (12PM), AIRBUS (12)

M1 – M42

T 1.2: Visual servoing for walking and multi-contact
INRIA (21), UNIROMA1 (10), DLR (6), CNRS (4)

M1 – M42

T 1.3: Balancing and multi-contact control
CNRS (25), DLR (12PM), AIRBUS (12)

T 1.4: Robust walking and standing
INRIA (21), UNIROMA1 (10), AIRBUS (12)
T 1.4: Robust walking and standing

Success:
Robust bipedal walking on relatively flat and sloped terrain, climbing stairs and stepping small obstacles and handling external perturbations (pushes) and light bumps (presence of nuts, screws, wires, cables...)

Y1 goals:
- DLR: First version of torque based walking implemented on TORO (simulation environment)
- INRIA & CNRS: First experiments of INRIA walking algorithm on HRP4 (stairs)
- UNIROMA1: Providing preliminary set of guidelines for integrating safety aspects in the walking. Main contributions planned for Y2&Y3
3.9 Work plan – WP2

Comanoid KOM March 2015

WP2 : Perception and localization
Inria (Lagadic), CNRS, DLR, UniRoma1, Airbus

WP2 Tasks
- **T2.1:** Localization and map generation – M1 → M36
  - CNRS/I3S: 25 MM
- **T2.2:** Object recognition – M1 → M36
  - CNRS/I3S: 18 MM
  - Airbus: 18 MM
- **T2.3:** Visual tracking – M1 → M30
  - Inria: 20 MM
- **T2.4:** Contact sensing – M6 → M42
  - UniRoma1: 18 MM
  - DLR: 9 MM
  - CNRS/Lirmm: 8 MM
- Total effort: 116 MM:
  - CNRS 43 + 8, Inria 20, UniRoma1 18, Airbus 18, DLR 9

WP2 Milestones and Deliverables
- **M2.1@M12:** First version of DLAM and object recognition provided with appropriate interfaces for DMU updates, visual servoing
  - Related to T2.1 and T2.2 (CNRS/I3S + Airbus)
- **M2.2@M18:** First version of visual tracking with interface to walking and multi-contact controllers
  - Related to T2.3 (Inria)
- **M2.3@M18:** First version of contact sensing with interface to multi-contact
  - Related to T2.4 (UniRoma1 + DLR + CNRS/Lirmm)
- **D2.1@M24:** Visual perception and contact sensing methods and software for demonstration on the Cobot platform
  - Related to all but T2.4 (CNRS/I3S + Inria + Airbus)
- **D2.2@M36:** Visual perception and contact sensing methods and software for demonstration on the Toro and HRP4 platforms
  - Related to all
- **M2.4@M36:** Advanced versions of vision and contact perception implemented
  - Related to all

T2.1: Localization and map generation
- M1 → M36. Partner: CNRS/I3S (25 MM)
  - RGB-D sensor
  - 3D/3D registration with DMU
  - Measure of success:
    - The 3D localization of the humanoid is provided in all parts of the assembly line.
    - The localization accuracy is 1% of the distance to the observed parts for the position and 1 deg for the orientation. Discrepancies between the DMU and the real environment are detected and the 3D model is correctly updated.
  - Y1: ensure 2.1@M12 (should be easy)

T2.2: Object recognition
- M1 → M36. Partners: CNRS/I3S (18 MM) + Airbus (18 MM)
  - Off-line objects learning with RGB-D
  - On-line object recognition and localization
  - Update the DMU from outliers
  - Measure of success:
    - Place recognition and part detection will be performed with a success rate of 95% or greater on a range of challenging test sequences. The accuracy of the position and orientation of the part obtained from the detection phase should be within 1% of the distance to the observed parts and 1 deg in orientation.
    - Y1: outliers detection (TBC)

T2.3: Visual tracking
- M1 → M30. Partner: Inria (20 MM)
  - An alternative to RGB-D and 3D localization: focus on particular parts
  - Measure of success:
    - The tracking of the visual features are accurate and robust enough so that the visual servoing tasks involved in WP1 are successfully achieved. The visual tracking is performed at 10 Hz.
  - Y1: start implementation for demonstration on the Cobot platform (8 + 0.5 MM in 2015)
T2.4: Contact sensing

- M8 -> M42. Partners: UniRoma1 (18 MM), CNRS/Lirmm (9 MM), DLR (8 MM)
  Contact detection, localization of the contact point, and contact force estimation
  from virtual force sensor (UniRoma1 + DLR)
  SynTouch solution (CNRS/Lirmm)
  - M2.3@M18: First version of contact sensing with interface to multi-contact
  - Measure of success:
  Contacts detected with a rate of false positive or false negative smaller than 5%.
  Contact point estimated with 1cm of accuracy for contacts with the static
  environment, and about 5cm for unintentional contacts with human operators or
  moving objects. Estimate of external contact forces with an error smaller than
  15%.
  - Y1:
3.10 Work plan – WP3

WP3: discussion and plan

WP3 in detail

<table>
<thead>
<tr>
<th>Work package number</th>
<th>Start date or standing event</th>
<th>WP</th>
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**UNIROMA1 responsibilities**

- WP3 leader (46 pm)
- T1.2: Visual servoing for planning and multi-contact (10)
- T1.4: Robust walking and standing (16)
- T2.1: Contact sensing (18)
- WP4 (18)
- WP5 (3)

**COMANOID vs SAPHARI**

- **humanoids vs manipulators (fixed-base or mobile): HRP-4 (position-controlled) and TORO (torque-controlled)**
- **humans in the workspace but no physical interaction**
- **COMANOID considers complex environments cluttered with humans, uneven terrain, difficult accessibility**
- **COMANOID uses on-board sensors**

**Objective: safety of humans, of the humanoid, of the environment**

- T3.1 Human-humanoid safe coexistence and physical interaction
- T3.2: Human safety issues in planning and control
- T3.3: Safe falls of humanoid robots
- T3.4: Humanoid safety procedures and assessment in operation sites

**T3.1 Human-humanoid safe coexistence and physical interaction**

- UNIROMA1 (21)
- Detection of potential collisions (humans… but also obstacles) or general hazard
- Use on-board sensors, need gazing strategy
- Collision avoidance strategies
- No fixed base, need to maintain balance
- Reaction strategies to unexpected contacts (collisions)
- Contact sensing from T2.4 for discriminating between expected/unexpected contacts
- Collaboration on expected contacts
  - As in SAPHARI but outside COMANOID demo scenario

**T3.2 Human safety issues in planning and control**

- UNIROMA1 (21), CNRS (4)
- Combine planning with reaction
- Human-related safety criteria
  - Predictability, legibility, comfort of handovers
- Include safety issues in multi-contact planning
- Guarantee conditions for implementing detection/reaction strategies

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T3.3 Safe falls of humanoid robots

- INRIA (22), CNRS (12), DLR (6)
- as falling may still occur, integrity of the robot, the humans and environment must be preserved
- failure detection and recovery
- predefined falling motions vs. on-line generation using available contacts

T3.4 Humanoid safety procedures and assessment in operation sites

- AIRBUS (4), UNIROMA1 (4)
- risk analysis
- take into account existing AIRBUS rules and practice
- safety procedures for humanoid deployment
- feedback expected on other WPs

Discussion on WP3, T3.1

- safety as an inner layer (avoidance/reaction)
- robot moves under a plan; may be walking in an open area or executing a non-gaited motion via multi-contact
- the robot is moving in a cluttered area and the plan will typically require the robot to get very close and even touch some obstacles (multi-contact surfaces)
- this means we cannot define a fixed safety area around the robot
- safety layer is activated by an alarm, i.e., detection of a situation which is (1) dangerous and (2) unexpected

Discussion on WP3, T3.1

- collision avoidance: humans vs. obstacles
- collision with humans: impossible to discriminate with pure contact sensing
- the alarm should be informative: direction, speed... (both for approaching obstacles and collisions)

Discussion on WP3, T3.1

- collision avoidance and reaction
  - need to maintain balance but can use stepping
  - can also establish new contacts
  - objective of avoidance and reaction may be (1) to stop safely, and give back control to the upper layers; or (2) locally deform the plan, until alarm goes off

Criticalities WP3, T3.1

- everything hinges upon robust alarms
  - vision-based difficult to detect what is unexpected based on, e.g., simple depth information
  - contact-based easier: based on area of contact
  - structure of upper layers unclear (yet)

WP3 deliverables and milestones

- vision-based alarm: based on distance (significant differences wrt the "nominal" scene) or more in general any kind of relevant new visual information in the environment
  - triggers collision avoidance
    - need to define gazing strategy
  - contact-based alarm: based on contacts and their classification as intentional (remember: multi-contact plans) or unexpected (collisions)
    - triggers collision reaction

- collision avoidance:
  - humans vs. obstacles
  - collision with humans: impossible to discriminate with pure contact sensing
  - the alarm should be informative: direction, speed... (both for approaching obstacles and collisions)

- collision avoidance and reaction
  - need to maintain balance but can use stepping
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WP3 measures for success

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<td>T1.2 Visual servoing for planning and multi-contact</td>
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- • 10 pm
- • “develop a module for vision-based navigation in relatively free areas” by extending corridor navigation

T1.2: Visual servoing for planning and multi-contact

- 10 pm
- • “develop a module for vision-based navigation in relatively free areas” by extending corridor navigation

T1.4: Robust walking and standing

- • 16 pm
- • general task objective: “obtain a reliable and safe walking behavior in the considered scenario”; declines as (1) robustness wrt perturbations (bumps, cables,...) plus (2) ability to reach the destination in spite of modifications in the scene (obstacles, humans)
- • safe avoidance of humans needs specific development, in terms of social constraints that can be passed to the robust walking module

T2.1 Contact sensing

- • 18 pm
- • our contribution: develop a virtual force sensor approach for contact detection, localization and force estimation
- • critical: do not rely on depth camera