Safe, Efficient and Integrated Indoor Robotic Fleet for Logistic Applications in Healthcare and Commercial Spaces

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grand agreement No 823887
Hospitals high commercial potential for logistic robotics

- **500+ person.months dedicated to no-added-value** delivery tasks
- Stringent building codes result in a structured navigation space for robots.
- Reliable communications infrastructure available.

Witness poor widespread acceptance by the market. Existing systems:

- require **costly infrastructure** installation
- do not **easily integrate** to corporate IT solutions;
- are not adequately shielded from cybersecurity threats,
- do not fully automate procedures and traceability of carried items
- are **limited on scope**, focusing only on delivery services.
ENDORSE addresses the technical challenges:

- Infrastructure-less multi-robot navigation,
- Advanced Human-Robot Interaction (HRI) for resolving deadlocks and achieving efficient sharing of space resources in crowded environments;
- Deployment of the ENDORSE software as a cloud-based service facilitating its integration, complying with GDPR data security requirements;
- Reconfigurable and modular hardware architectures. Integration of an e-diagnostic module for vital signs monitoring on a fleet of mobile robots, with connectivity to cloud-based EHR.
Cyber-Physical Systems and Uncertainty

Nacim RAMDANI
University of Orléans, at Bourges
agora.bourges.univ-orleans.fr/ramdani

Singular Logic, 12 February 2019, Athens.
Hybrid and Cyber-Physical Systems
Hybrid Cyber-Physical Systems

- Interaction discrete + continuous dynamics
- Safety-critical embedded systems
- Networked autonomous systems
Hybrid Cyber-Physical Systems

Operation in challenging environment, requires ...

- Verification
  - Numerical proof, or
  - Falsification via counter-example
- Synthesis
  - « Correct by construction » ...
- Monitoring, FDI
  - Complete state reconstruction
  - Worst-case scenario
  - « Secure » state estimation
Hybrid Cyber-Physical Systems

### Modelling → hybrid automaton (Alur, et al. 1995)

- Non-linear continuous dynamics
- Nonlinear guards sets
- Nonlinear reset functions
- Bounded uncertainty

\[ H = (Q, D, P, \Sigma, A, \text{Inv}, \mathcal{F}) \]

**Continuous dynamics**

\[
\begin{align*}
\text{flow}(q) &: \quad \dot{x}(t) = f_q(x, p, t), \\
\text{Inv}(q) &: \quad \nu_q(x(t), p, t) < 0,
\end{align*}
\]

**Discrete dynamics**

\[
\begin{align*}
A \ni e &: \quad (q \rightarrow q') = (q, \text{guard}, \sigma, \rho, q'), \\
\text{guard}(e) &: \quad \gamma_e(x(t), p, t) = 0,
\end{align*}
\]

\[ t_0 \leq t \leq t_N, \quad x(t_0) \in X_0 \subseteq \mathbb{R}^n, \quad p \in P \]
Example: the bouncing ball

initial conditions
\( x = 10, v = 0 \)

discrete transition
jump
\( x = 0 \)
\( v' := -v \)

\[ \dot{x} = v \]
\[ \dot{v} = -9.81 \]
\( x \geq 0 \)
Secure Monitoring & State Estimation
Bounded-error state estimation

- Unknown but bounded-error framework

**Hypothesis**

Uncertainties and errors are bounded with known prior bounds

**A set of feasible solutions**

\[ S = \{ p \in \mathbb{P} | f(p) \in \mathbb{Y} \} = f^{-1}(\mathbb{Y}) \cap \mathbb{P} \]
**SIVIA (Jaulin et al., 93)**

- Inclusion test. Branch-&-Prune. Branch-&-Bound

\[
S = f^{-1}(Y) \cap P \\
\rightarrow \underline{S} \subseteq S \subseteq \overline{S}
\]
SIVIA (Jaulin et al., 93)

- Inclusion test. Branch-&-Prune. Branch-&-Bound

\[ S = f^{-1}(Y) \cap P \]

\[ \rightarrow \bar{S} \subseteq S \subseteq \bar{S} \]

**Inclusion test:**

- \( f([p]) \subseteq Y \Rightarrow [p] \subseteq S \)
- \( f([p]) \cap Y = \emptyset \Rightarrow [p] \not\subseteq \bar{S} \)

otherwise *bisect* . . .
**Interval Analysis: Set Inversion**

- **SIVIA (Jaulin et al., 93)**

  - Inclusion test. Branch-&-Prune. Branch-&-Bound

  \[ S = f^{-1}(Y) \cap P \]

  \[ \rightarrow \bar{S} \subseteq S \subseteq \overline{S} \]

  *Inclusion test:*

  \[ f([p]) \subseteq Y \Rightarrow [p] \subseteq S \]

  \[ f([p]) \cap Y = \emptyset \Rightarrow [p] \not\subseteq S \]

  otherwise *bisect* ...
Interval Analysis : Set Inversion

- SIVIA (Jaulin et al., 93)
- Inclusion test. Branch-&-Prune. Branch-&-Bound

\[ S = f^{-1}(Y) \cap P \]
\[ \rightarrow S \subset S \subset \overline{S} \]

Inclusion test:
\[ f([p]) \subseteq Y \Rightarrow [p] \subseteq S \]
\[ f([p]) \cap Y = \emptyset \Rightarrow [p] \not\subseteq \overline{S} \]
otherwise bisect...
q-Relaxed intersection

\[
\bigcap X_i = \bigcap X_i
\]

\[
\bigcap X_i = \bigcap X_i
\]

\[
\bigcap X_i = \bigcap X_i
\]
Secure Localisation

- **Robot localisation via Trilateration**
  - Can measure the distance to a beacon.
Secure Localisation

1 beacon

Figures obtained using PYIBEX tool.
benensta.github.io/pylbex
2 beacons

Figures obtained using PYIBEX tool. benensta.github.io/pylbex
Secure Localisation

4 beacons

Figures obtained using PYIBEX tool.
benensta.github.io/pyibex
Secure Localisation

4 beacons
1 corrupted

Figures obtained using PYIBEX tool.
benensta.github.io/pylbex
Secure Localisation

1-relaxed Intersection

Figures obtained using PYIBEX tool. benensta.github.io/pylbex
1-relaxed Intersection

Spurious datum identified

Figures obtained using PYIBEX tool. benensta.github.io/pylbex
Bounded-error state estimation

- **Idealized algorithm:** Prediction / Correction steps (Kieffer, et al, 01)
- **Objective:** Characterize sets of state consistent with available information
**Idealized algorithm:**
Prediction / Correction steps (Kieffer, et al, 01)

**Objective:** Characterize sets of state consistent with available information

Discrete-time state equation:
\[ x_{k+1} = f_k(x_k, w_k, u_k). \]

Observation equation:
\[ y_k = h_k(x_k) + v_k, \quad k = 1, \ldots, N. \]

Problem:
Evaluate state \( x_k \) using all available information.
Bounded-error state estimation

- **Idealized algorithm:** Prediction / Correction steps (Kieffer, et al, 01)

- **Objective:** Characterize sets of state consistent with available information
Idealized algorithm:
Prediction / Correction steps (Kieffer, et al, 01)

Objective: Characterize sets of state consistent with available information
Bounded-error state estimation

- **Idealized algorithm:** Prediction / Correction steps (Kieffer, et al, 01)

- **Objective:** Characterize sets of state consistent with available information
Bounded-error state estimation

- **Idealized algorithm:** Prediction / Correction steps (Kieffer, et al, 01)

- **Objective:** Characterize sets of state consistent with available information
Bounded-error state estimation

- **Idealized algorithm:** Prediction / Correction steps (Kieffer, et al, 01)

- **Objective:** Characterize sets of state consistent with available information
M. Maïga, N. Ramdani, L. Travé-Massuyès, C. Combastel,

Verification
Verification of Hybrid Systems

- Verification
  - Modelling:
  - Property specification:
  - Verification algorithm: Reachability of unsafe regions
  - Hybrid / Continuous reachability
Aircraft traffic control (Tomlin, et al.)

Collision possible!

Reachable sets

Time

disturbance
Synthesis of correct-by-construction control systems
Correct-by-construction parametric synthesis

Reach-Avoid problem
Parametric synthesis

Reach-Avoid problem

\[ S = \left\{ x_0 \in X_0 \mid \begin{array}{l}
(\forall t > t, \{\varphi_q(t, x_0), q(t, x_0)\} \in \text{Target}) \\
\wedge \\
(\forall t > t_0, \forall q, \varphi_q(t, x_0) \cap \text{Unsafe}_q = \emptyset)
\end{array} \right\} \]
Synthesis of Hybrid Systems

Parameter Synthesis with Nonlinear Hybrid Systems
Initial velocity of a bouncing ball.
Initial velocity of a bouncing ball.
Initial velocity of a bouncing ball.
Synthesis of Hybrid Systems

Initial velocity of a bouncing ball.
Detecting and localizing events

Improved and enhanced version

Bouncing ball in 2D.
Detecting and localizing events

Improved and enhanced version

Bouncing ball in 2D.
Reachability analysis

Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Reachability analysis

Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Synthesis of Hybrid Systems

Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Synthesis of Hybrid Systems

Validation

Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Synthesis of Hybrid Systems

Validation

Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Figures obtained using MAGIC-CPS tool developed by nacim.ramdani@univ-orleans.fr
Secure & Robust Optimization
Dispatch problems arising in scheduling of power generation and battery charge cycles.

(a) Demand Prediction Profile.

(b) Profiles of Power Generation and Battery Charge Cycles.
Dispatch problems arising in scheduling of power generation and battery charge cycles

(c) Demand Prediction Interval. (d) Intervals of Power Generation and Battery Charge Cycles.
Dispatch problems arising in scheduling of power generation and battery charge cycles
Dealing with uncertainty when scheduling power generators

Power-distribution network operators schedule turning on/off of generators to...

Novel UC approach that deals with each timeslot of the scheduling period independently.

However, standard UC approaches for scheduling generators deal with uncertainties such as...

Benefit of this approach:

- Considers potential generator failure
- Increases reliability
- Lowers cost
- Avoids power surplus or shortage
- Decreases complexity for large systems

Box-based Temporal Decomposition of Multi-period Economic Dispatch for Two-stage Robust Unit Commitment
Youngchae Cho, Takayuki Ishizaki, Nacim Ramdani, and Jun-ichi Imura
Journal: IEEE Transactions on Power Systems  DOI: 10.1109/TPWRS.2019.2896349
Future work
Resource-aware algorithms

- Event/Self-triggered sampling for estimation

Combine Resource-aware & Secure algorithms
Correct-by-construction Design

- Specification + translation for verification
  - of existing code!

- Scalability for non-linear & hybrid systems
  - Parallelisation
  - Abstraction
  - Compositional approaches

- Extension to stochastic hybrid systems
Thank you!
Selected References

**Robust Estimation with Hybrid Systems**


**Validation of Hybrid Systems**


**Correct-by-Construction Design**


**Robust Unit Commitment**