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HUMAN ROBOT INTERACTION

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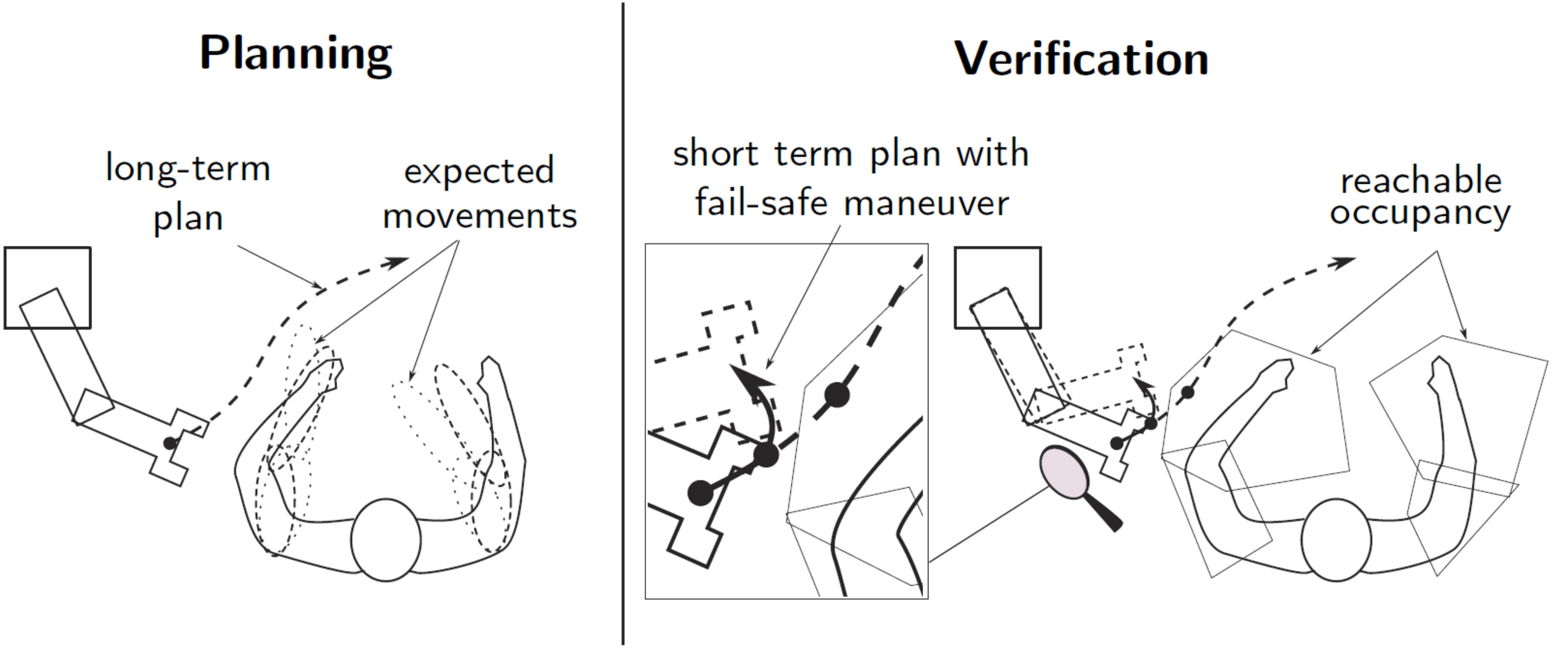
Motivation

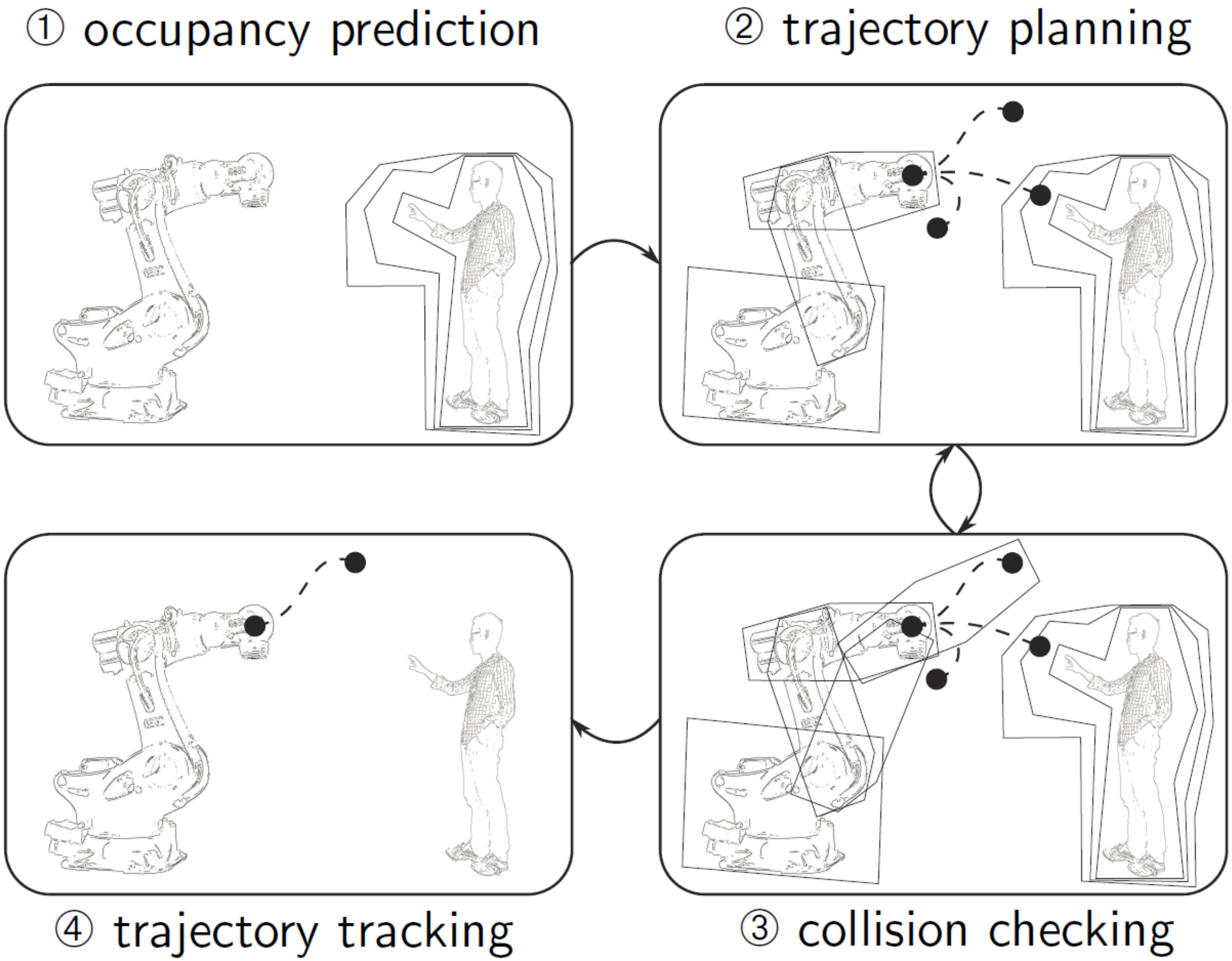
Part 1: Online Verification (Matthias)

Part 2: Application to Food Industry (Geoff)

Basic Principle

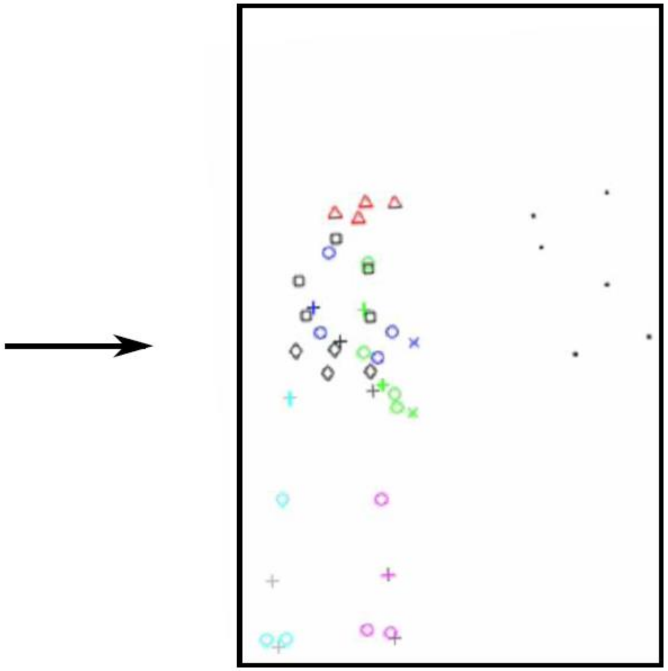


Required Techniques

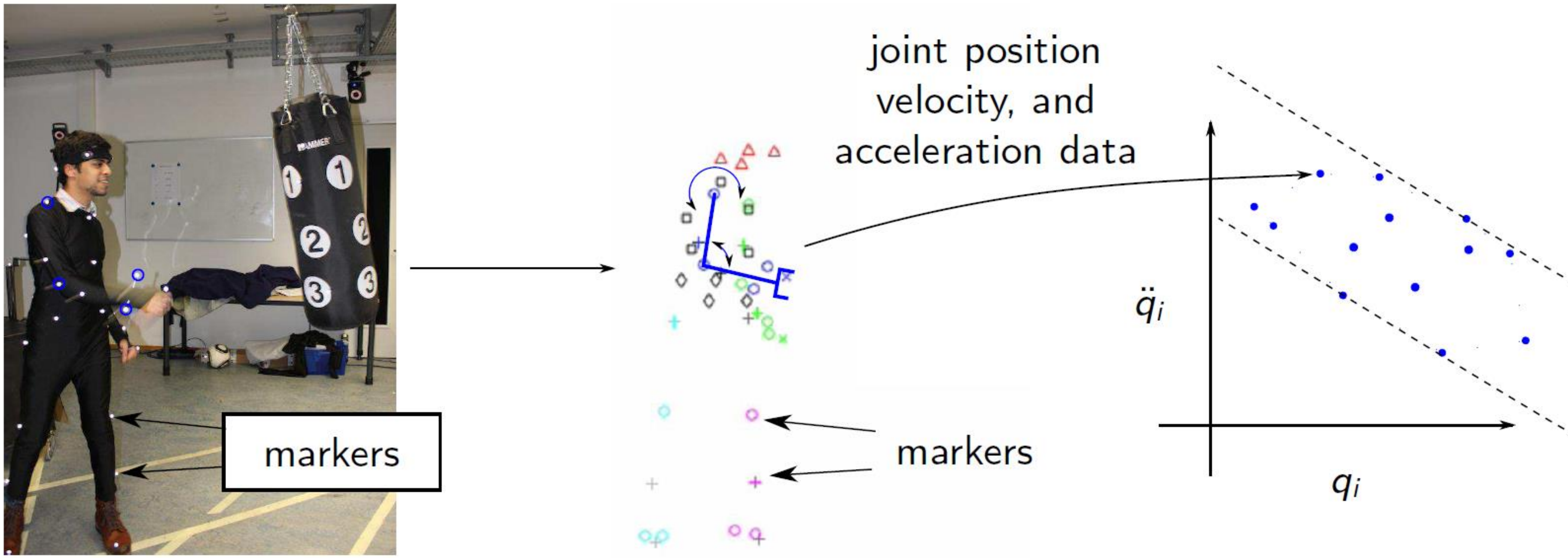


Data Acquisition for Modelling Humans

- Collaboration with Chair of Ergonomics at TUM.
- 38 persons: 12 female and 26 male.
- Ranging in age between 18 and 49 with a median age of 24.
- 50% do 3 or more hours of sport a week.



Bounding Parameters of Motion



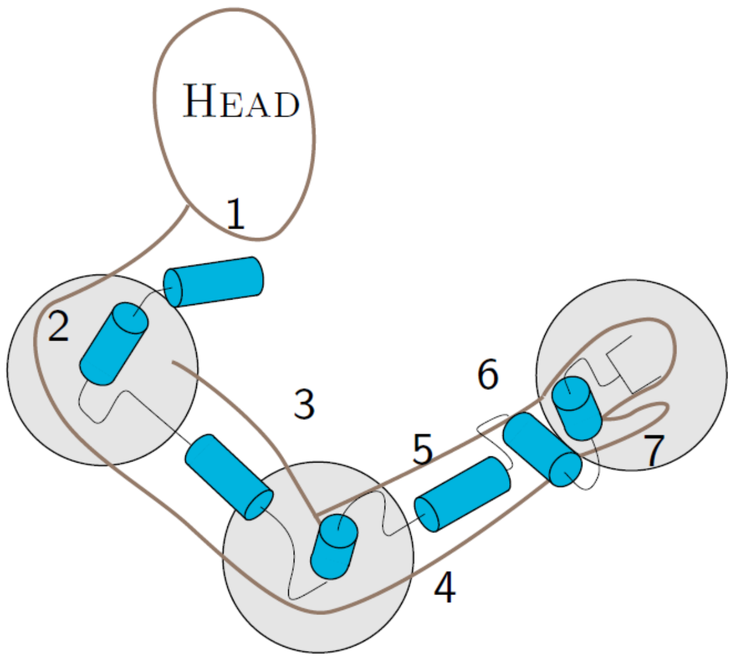
(a) Motion Capture experiments

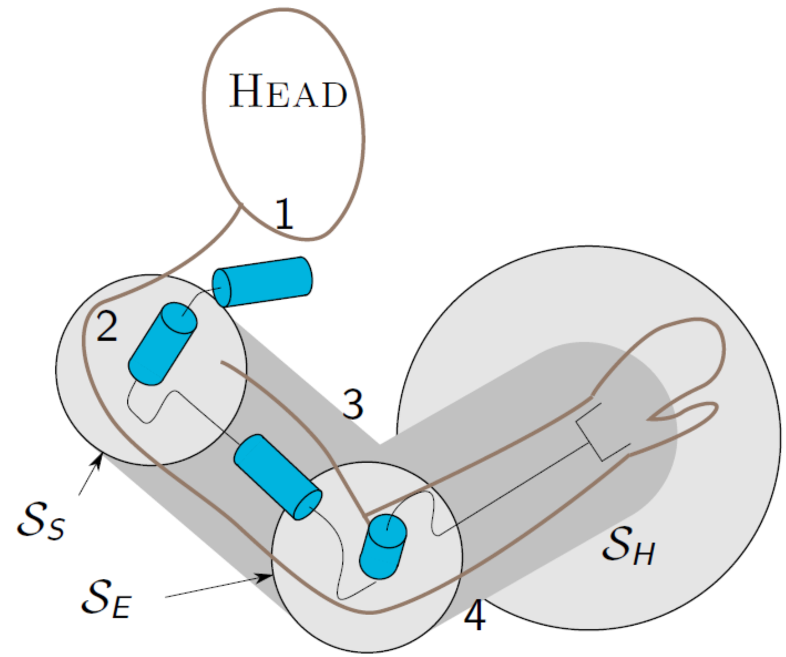
(b) Fitting to Kinematic model

(c) Bounding of joint angles velocities and accelerations

Kinematic Model

- Human arm modeled as 7 degree of freedom (DOF) kinematic chain (left).
- We neglect wrist and hand movement since they do not contribute much to the occupancy (right).





Dynamic Model

We consider three types of models whose results are combined:

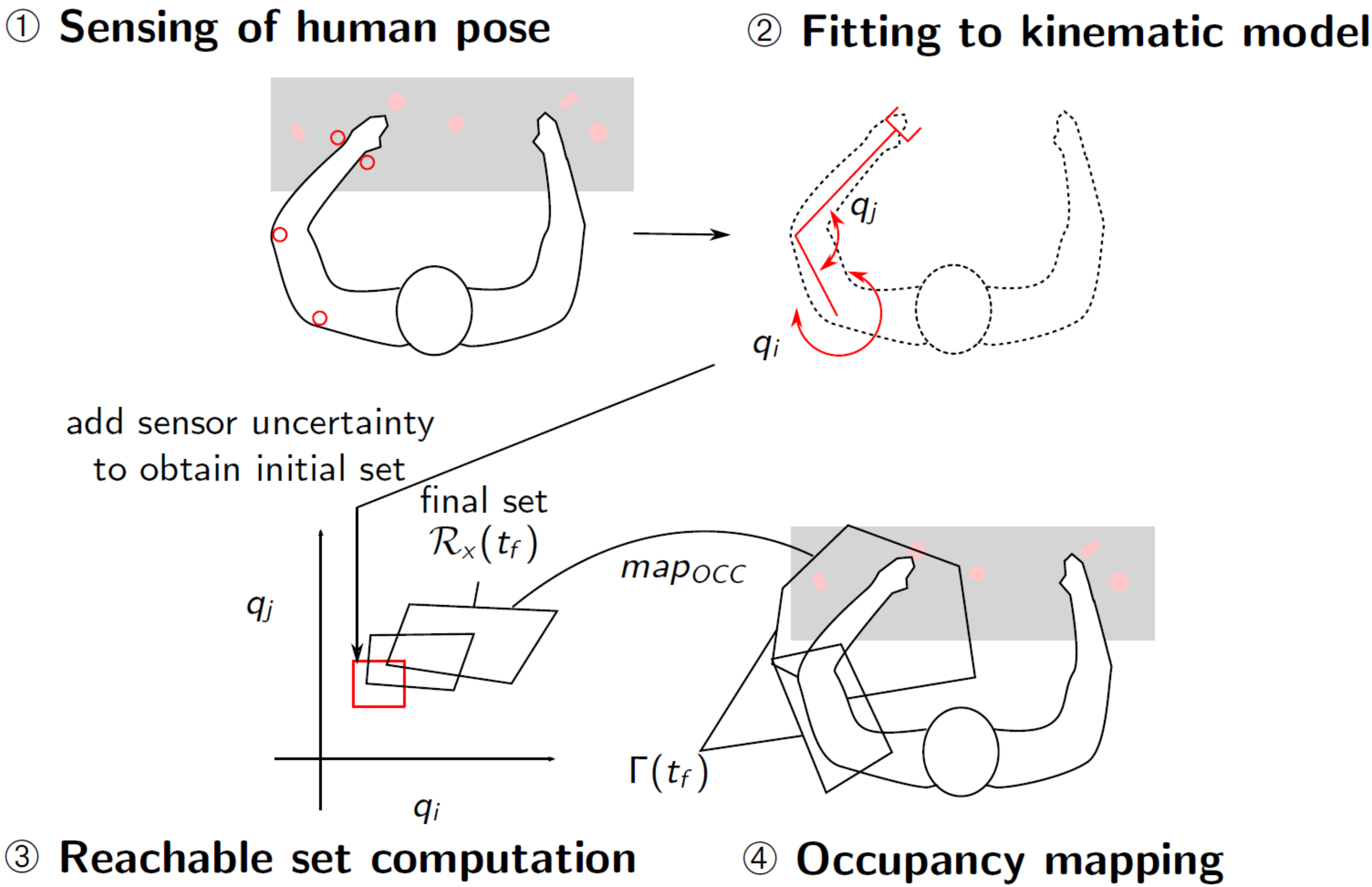
1. a 0^{th} order model: $\mathcal{R}_{\mathbf{q}}^{(0)}(t) := [q_{\min}, q_{\max}]$
2. a 1^{st} order model: $\mathcal{R}_{\mathbf{q}}^{(1)}(t) := Q(0) \oplus [\dot{q}_{\min} t \;,\; \dot{q}_{\max} t]$
3. a 2^{nd} order model: $\mathcal{R}_{\mathbf{q}}^{(2)}(t)$ based on acceleration as a function of state

$$\begin{bmatrix} \dot{\mathbf{q}} \\ \ddot{\mathbf{q}} \end{bmatrix} = \dot{\mathbf{x}} \in \begin{bmatrix} 0 & I \\ & C \end{bmatrix} \mathbf{x} \oplus \begin{bmatrix} \mathbf{0} \\ [\mathbf{u}_{\min}, \mathbf{u}_{\max}] \end{bmatrix}.$$

(Minkowski addition $A \oplus B = \{a + b | a \in A, b \in B\}$)

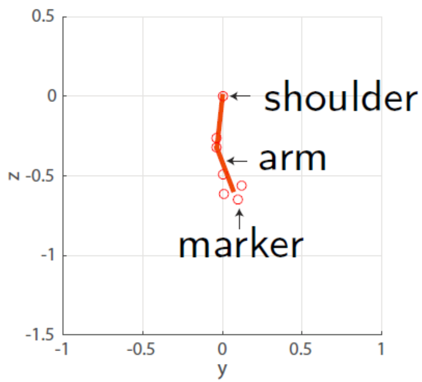
The C matrix is optimized to tightly predict the behavior based on measurements.

Online Prediction

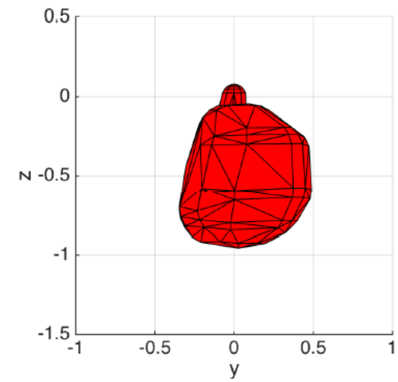


Example

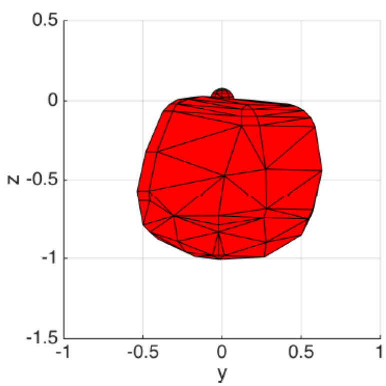
Initial position



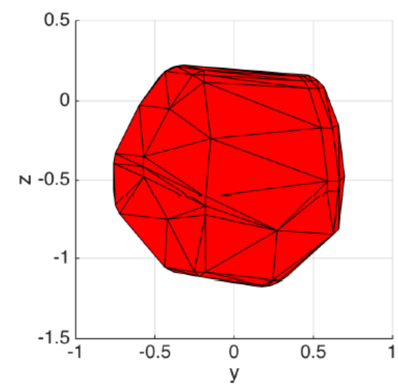
Prediction for $t = 16.7$ ms



Prediction for $t = 33.3$ ms



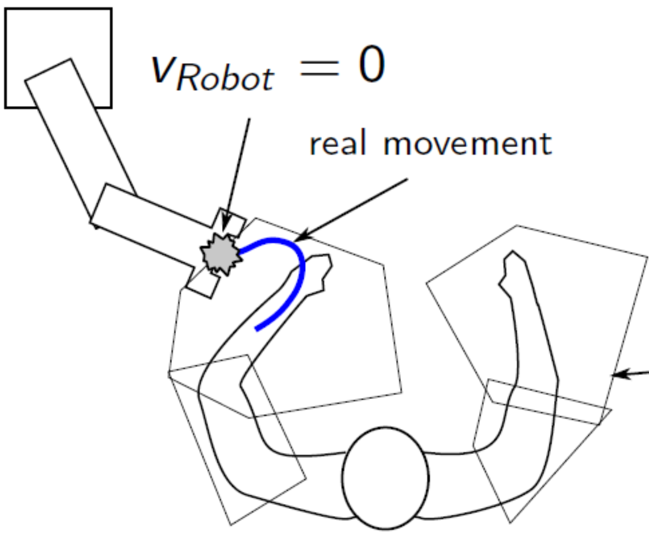
Prediction for $t = 50.0$ ms



Prediction horizon: 0.05 seconds (50 ms)
Computation time: 0.0037 seconds (3.7 ms) $\rightarrow$ faster than real time.

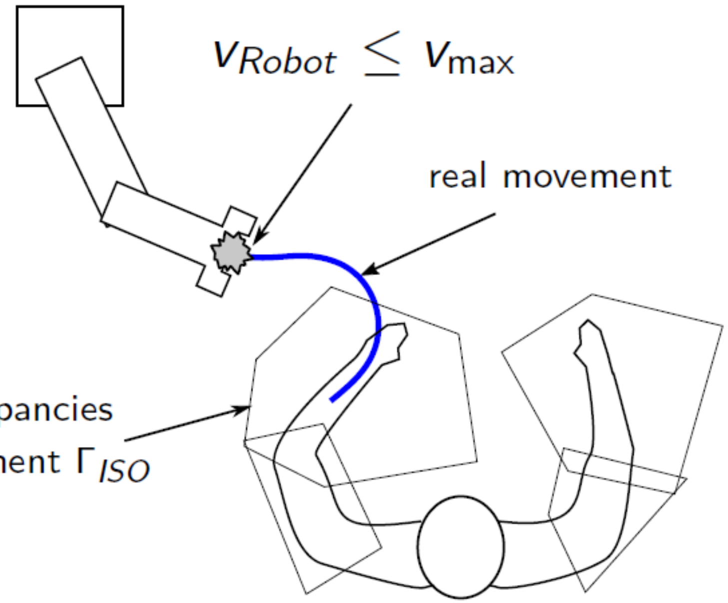
Extension Using a Twofold Safety Approach

Stationary criterion



robot guaranteed stopped
when colliding for
max $1.6 \frac{m}{s}$ of human

Reduced speed criterion



robot guaranteed below max velocity
when colliding for
all human movements

Real Experiments

Human Robot Collaboration in the Food Industry

Automation in the Food Industry

- Many tasks have been automated
  - Mainly in the 0.7% of large food manufacturers
  - Mainly using hard automation and excluding workers
- Little penetration of automation in the 99.3% of SME food manufacturers
  - Lots of low skilled labour with low retention rates
  - Low volume, frequent product change food assembly / transfer

Challenges in the Food Industry

- Dysfunctional supply chain
- Low batch volumes
- Short / unpredictable product life
- Short payback expectations
- Difficult product handling / food hygiene
- Low R&D investment (0.24% turnover)
  - Most on product development not process
- Low IT support capability
- Lack of space
- Lack of automation awareness

GRAIL ROBOT – KEY DRIVERS

- Food Industry needs ultra-flexibility
  - Task driven (specify end product not how to build it, i.e. no programming)
- Needs to work alongside humans
  - Space constraints in typical food SME (cannot afford space for guarding): Provable safety!
  - Needs to be able to be moved as flexibly as human
- Needs to be as efficient as human
  - Low overheads
  - Optimisation of picking and placing strategy

Specific Challenges of Safe Collaborative Systems

- (Relatively) high speed operation
- Low cost system = low cost (but reliable) sensors
- Space constraints = Overlapping workspaces
- Need for flexible operations
- Need to automatically recover from safety "shutdowns"

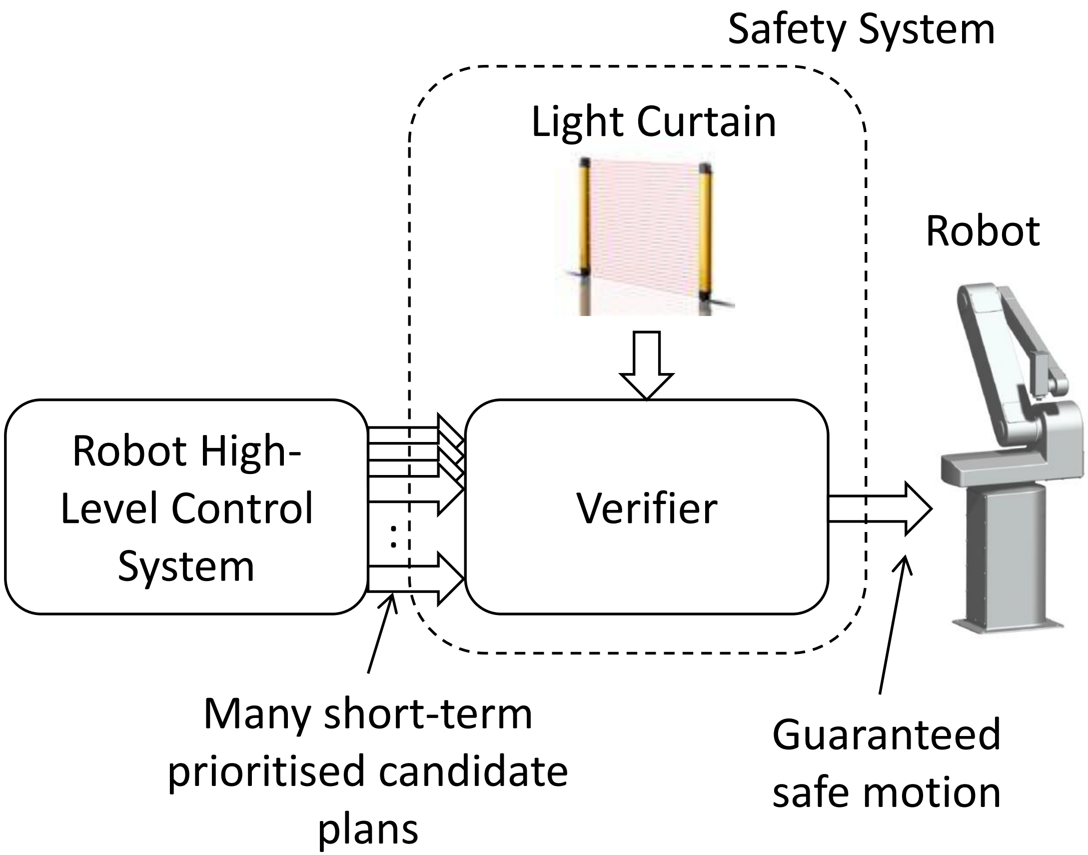
Application of the UnCoverCPS Approach for a Food Industry Robot

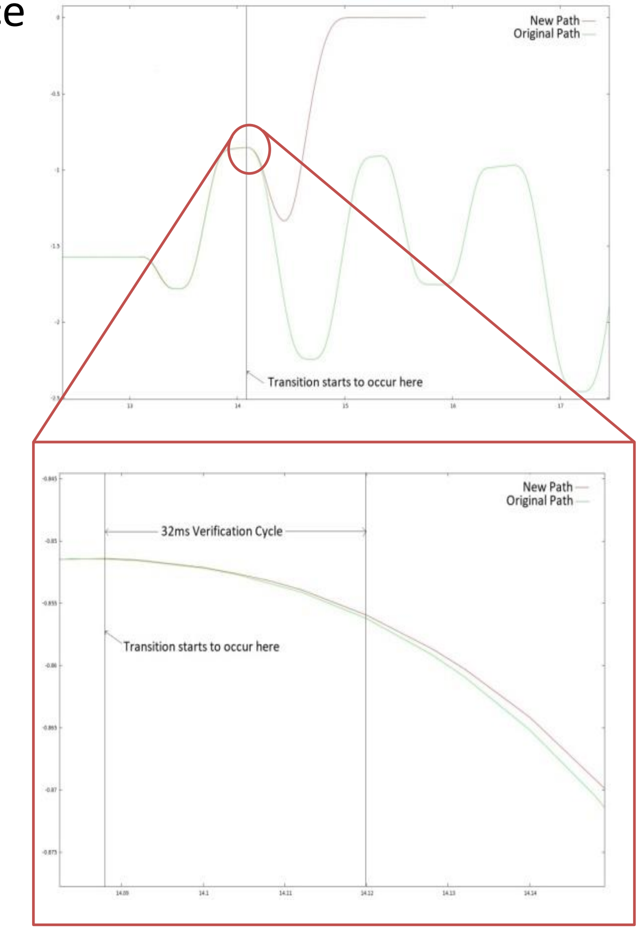
Overview of the GRAIL Robot System

- GRAIL Robot is tasked not programmed
  - Vision system driven
  - Adapts to the task
  - Non-predictable behaviour (for human)
- Safety is a key consideration
  - Lightweight but fast (60 picks per minute)

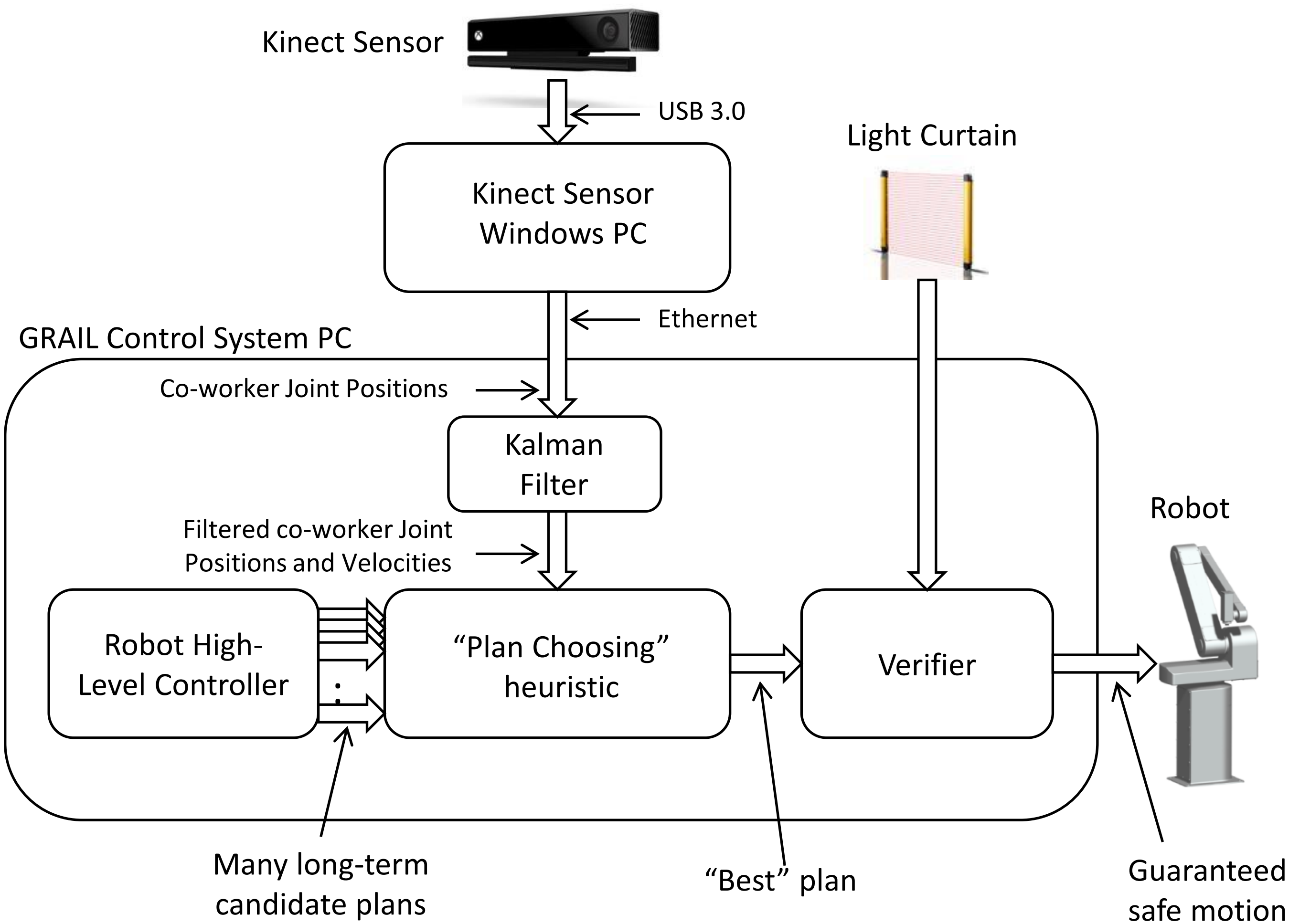
Grail Robot System using Verifier Alone

- First version had verifier “simply” choosing the safest path
- To be reactive verifier cycles were short
- However, nearly as all plans were similar = no choice

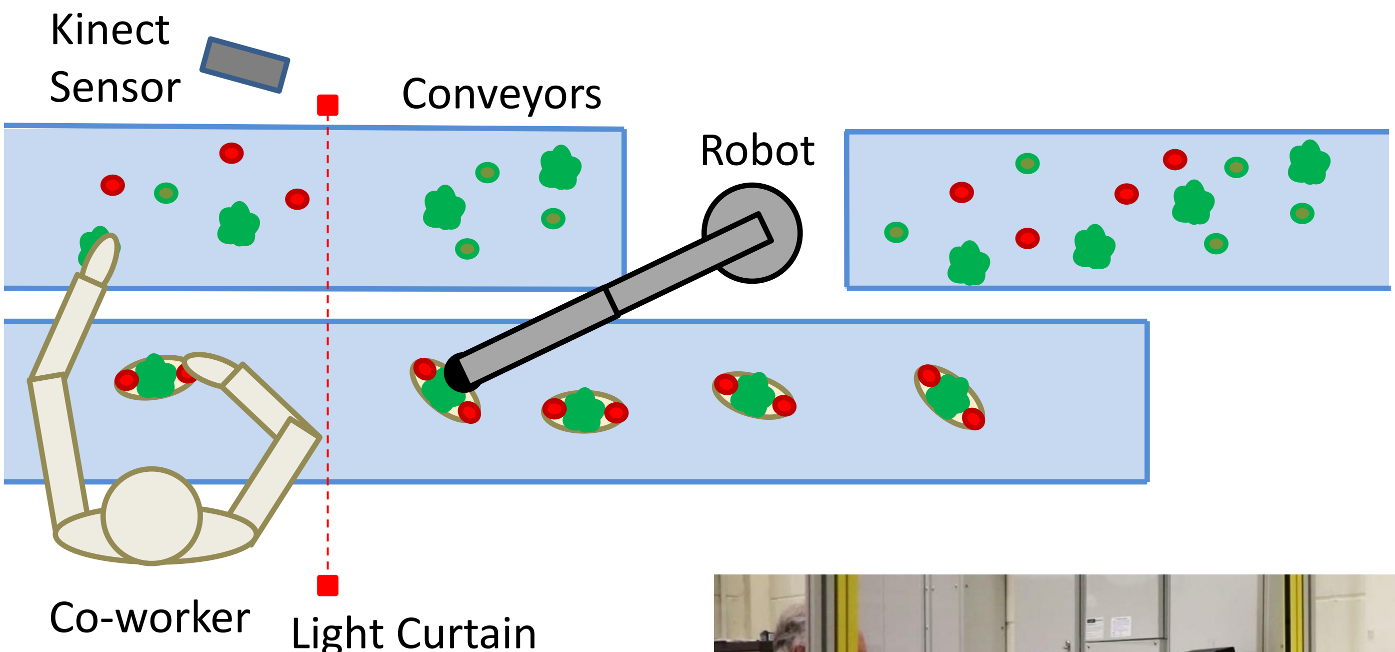




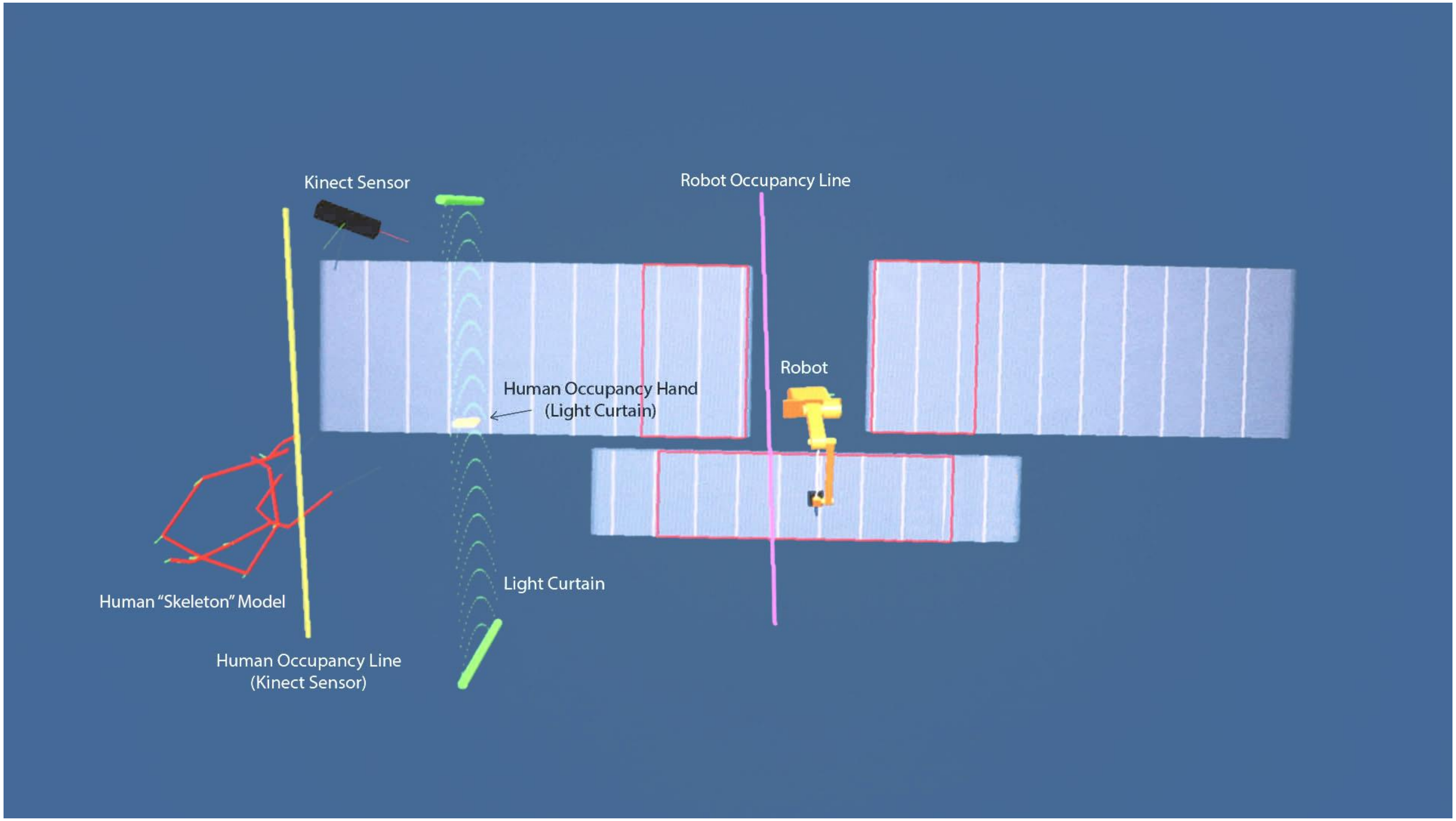
The Plan Choosing Heuristic - 2



Physical Implementation



The Test Bed Overview



The Plan Choosing Heuristic - 4

- The Plan Chooser currently chooses a plan bases on a number of metrics
  - How close the ingredients and bases are to the ends of the conveyors.
    - Ingredients are potentially wasted if they reach the end of the in-feed conveyors.
    - Bases are wasted if they reach the end of the out-feed conveyor incomplete.
  - The time taken to execute a given plan.
    - Shorter plans should be favoured since they allow the robot to carry out more useful operations while the product is within reach.
  - The distance between the predicted co-worker occupancy region and the robot occupancy region
    - Greater clearance means that the plan is more likely to be executed successfully without interruption due to an incursion of a co-worker.

The Plan Choosing Heuristic - 5

- There are three distinct regions for the occupancy of the co-worker(s):
  - Completely behind the Light Curtain
  - Between the Light Curtain and the Robot Occupancy region
  - Inside the Robot Occupancy Region

- To maximise throughput, these different regions could require a different approach to using the metrics.

The Plan Choosing Heuristic - 6

- The Plan Chooser combines the occupancy regions and the plan metrics by means of a weighted sum to generate on overall figure of merit. The weightings used in the following trials are shown below:

	Human-Robot Proximity	Proximity to Conveyor Ends	Plan Length
Co-worker is Completely Behind Light Curtain	0.0	0.001	-0.1
Co-worker is Between Light Curtain & Robot	0.0	0.001	-0.1
Co-worker and Robot's Occupancy Regions overlap	1.0	0.0	-0.01

- The scaling of each metric is different since they are measured in different units.
- The weights can be positive or negative since some metrics are better for larger numbers, whereas others are better for smaller numbers.
- The weights have been made easily configurable so that trials can be performed to optimise the results.

Conclusions

- Conclusions
  - The UnCoverCPS approach can provide guaranteed safety for operations with overlapping human-robot operation
  - Using simple safety sensors imposes significant restrictions on the applicability of the approach
    - A more sophisticated safety sensor (e.g. SafetyEye) would allow a more complete implementation of the approach
  - Providing a non-safety movement prediction system greatly enhances the flexibility of the system and therefore overall productivity
  - The UncoverCPS cannot be applied as a simple “end filter” or “wrapper”
    - Parts of the robot code will have to be developed to at least SIL 2
    - These cannot share computing resources with non-SIL developed code

Future Work for Human-Robot Collaboration Use Case

- Future Work
  - Evaluate alternative co-worker prediction algorithms to see if performance can be improved by using more sophisticated methods.
  - Optimise the weightings of the Plan Chooser to achieve maximum throughput
    - Perhaps perform automatic optimisation using Monte Carlo methods
    - Possibility for learning algorithm to optimise to the style of the worker
  - Perform evaluation of the benefits of incorporating the Plan Choosing Heuristic versus the Verifier alone
  - Evaluate the implications of implementation on a commercial robot system