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Mobile Robotic
Strawberry Monitoring and Harvesting
in Precision Indoor Farms

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Based on:

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- ❑ Strawberry fruit harvesting
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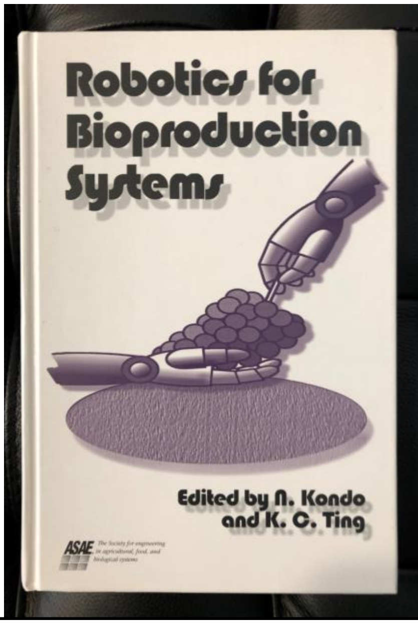
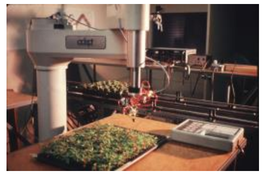
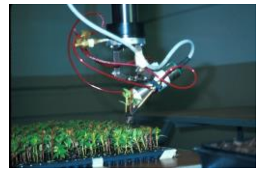
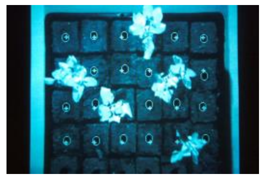
Introduction – Once upon a time….









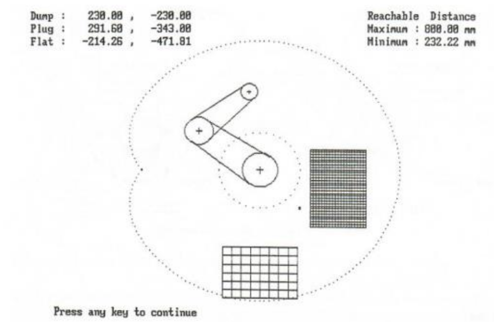


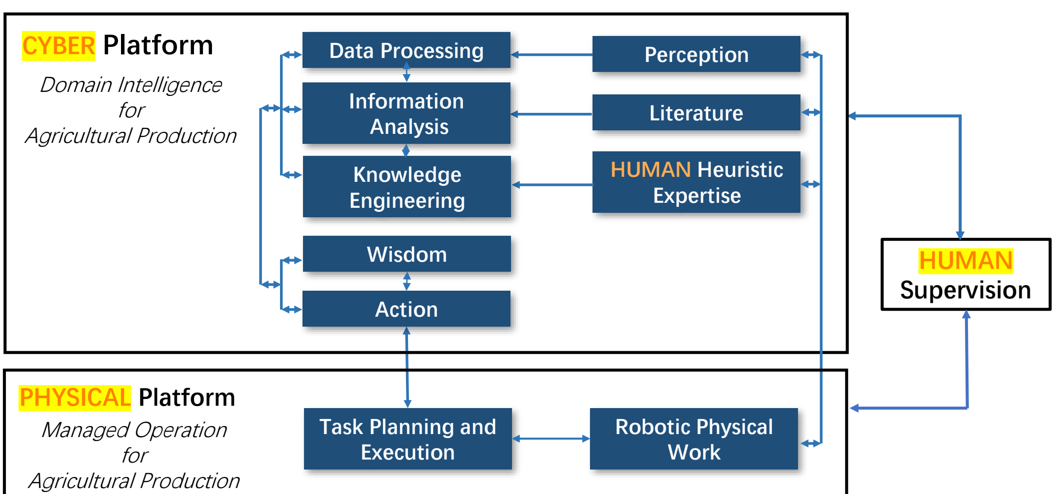
Figure 12.3. Stationary display of a workcell layout.

Published by ASAE (currently ASABE), 1998

Research conducted at Rutgers University, 1986-1992

Introduction – Recent and future

Scope of Intelligence Driven and Empowered Agricultural Systems (IDEAS) through HUMAN supervised (CYBER-PHYSICAL) Systems



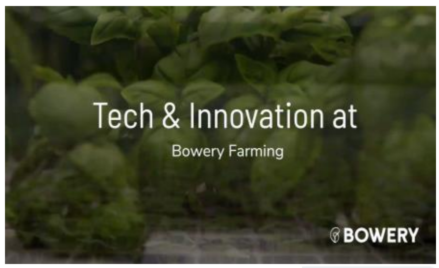
Introduction – Precision indoor farms

❑ Background

Rapid development in the US, East Asia, and Europe since 2018

❑ Core technologies

Automation, Robotics & Digitalization



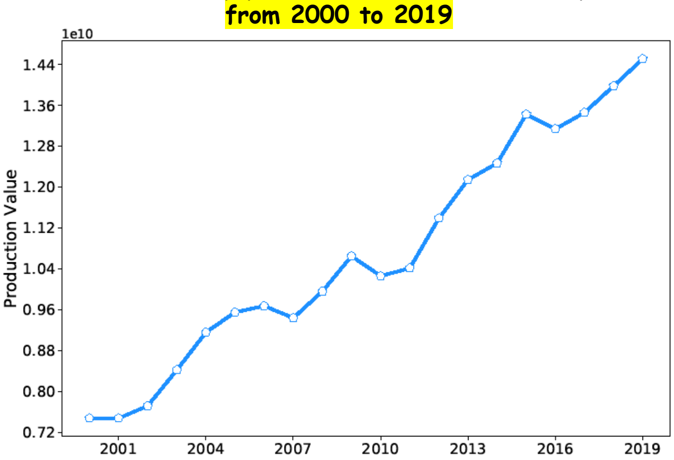
infarm — GER 2021.12 $200 million

BOWERY — US 2021.5 $300 million

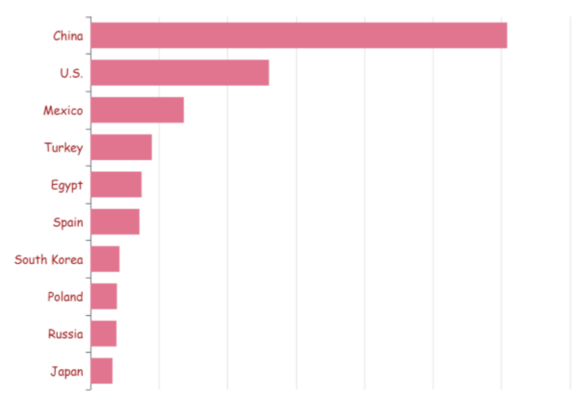
Plenty® — US 2022.1 $400 million

Introduction – Strawberry production

Global strawberry production value increased by 94% from 2000 to 2019



Top 10 producing countries in 2019
(in 1,000 metric tons)



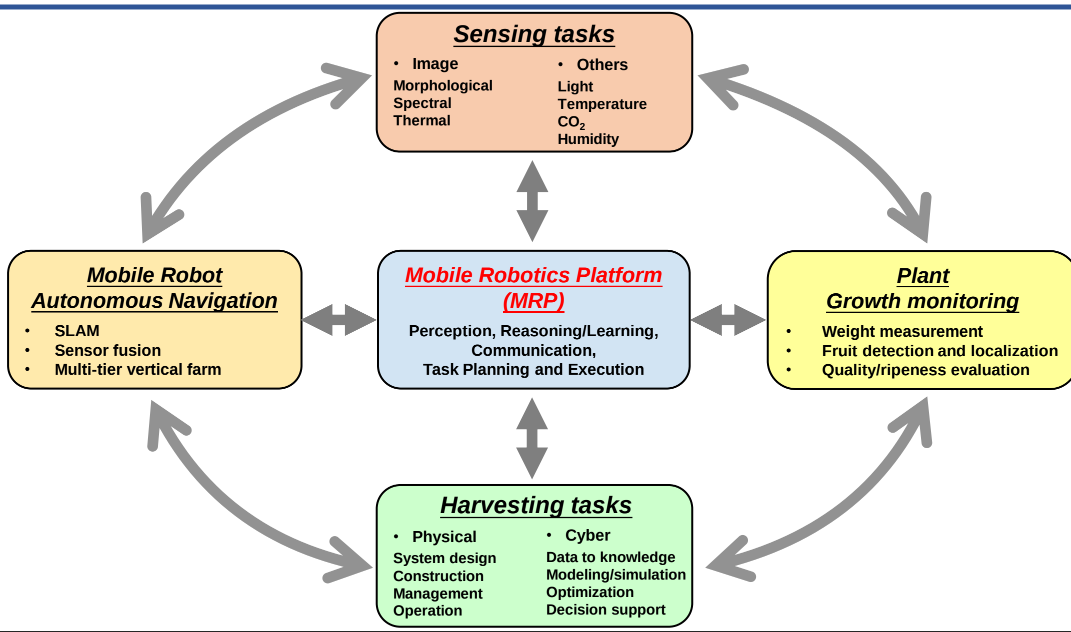
Repetitive tasks		High labor costs		
Soft fruit	⇨	Bruise easily	⇨	**Robotics**
Non-climacteric fruit		Selective harvesting		

Source: FAO

Introduction – Overall research goals

- ❑ To develop a Mobile Robotics Platform (MRP) for strawberry cultivation tasks leading towards Intelligent Agricultural Systems
- ❑ To conduct efficient near-real time monitoring of all individual strawberry plant and fruit within a whole precision indoor farming system, PIFS (i.e. quasi IoT)
- ❑ To perform production estimation and harvesting planning and execution for a whole PIFS
- ❖ *To provide spatial-temporal data support for Genetics, Environment, and Management (GEM) research on interaction mechanisms of plant, environment, automation, and cultural tasks*

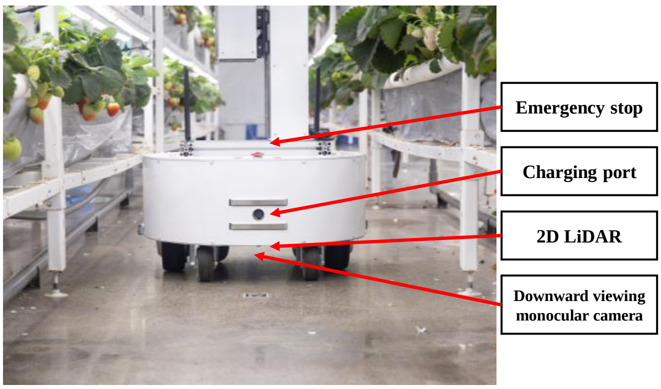
Introduction – Systems analysis of research concept



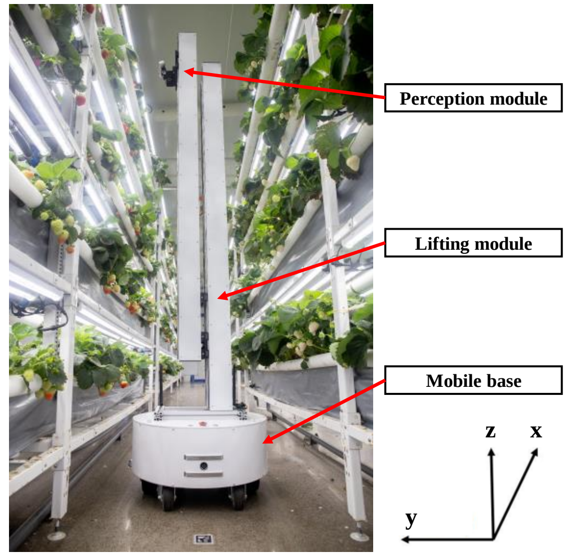
Mobile robotics platform (MRP)

Hardware

1) **Mobile base - Differential wheeled robot**
2) **Multilayer perception robot**



Mobile base



MRP

MRP navigation

Navigation system

1) Sensors

Localization：Camera+IMU+Encoders

Obstacle avoidance：2D LiDAR

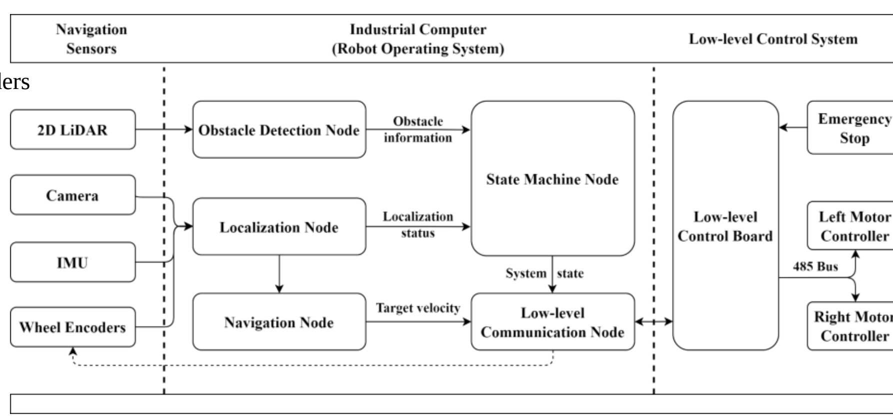
2) Operating system

5 ROS nodes

Output：Target velocity

3) Low-level control system

Output：2 motor speeds



Navigation system architecture

MRP navigation

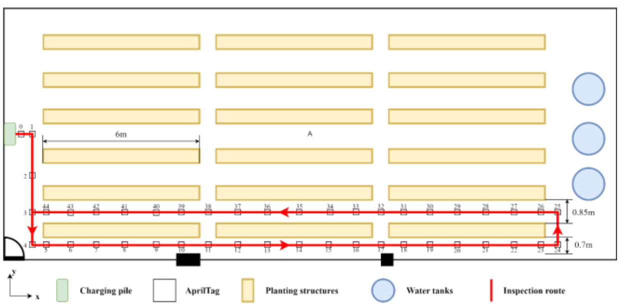
Navigation approach – AprilTag and Inertial based navigation (ATI navigation)

1) Mapping

Data fusion: AprilTag + IMU + Wheel encoders

2) Path planning – Breadth-first search (BFS) algorithm

3) Control – PID controller + Differential motion model



Schematic diagram of the experimental scene and inspection route

The MRP is being charged in the commercial strawberry factory

MRP navigation

Experiments

1) Objectives

① The impact of loop optimization on ATI navigation

② The advantage of ATI navigation in PIFs

2) Methods

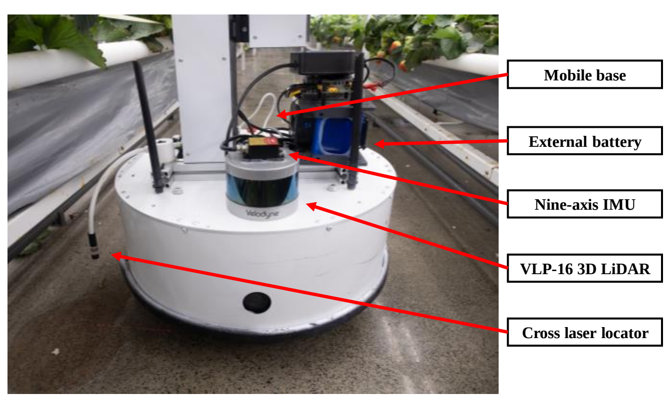
① LIO-SAM（Tightly coupled Lidar-Inertial odometry）

② ATI navigation w/o loop optimization

③ ATI navigation w/ loop optimization

3) Evaluation

Mapping trajectories



Shan T., et al., IROS 2020

MRP navigation

Results

1) Loop closing optimization (Red vs Blue)

① To eliminate the cumulative errors

② To obtain a consistent and undistorted trajectory

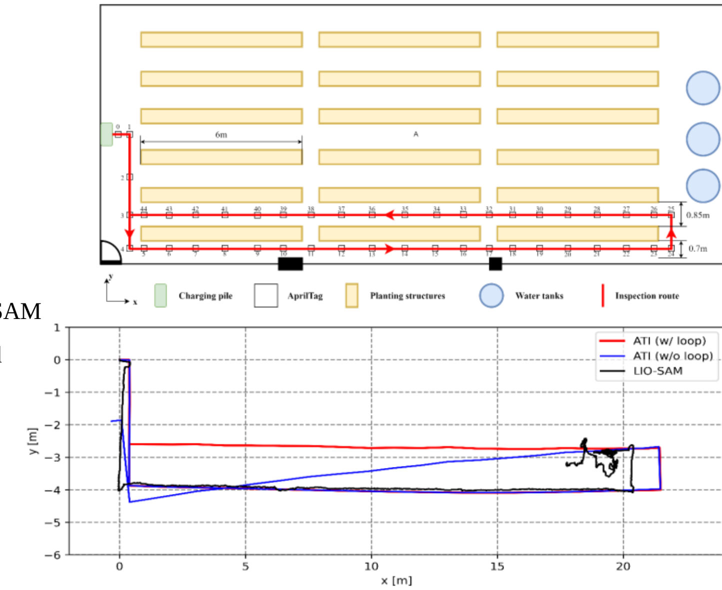
2) ATI navigation (Red vs Black)

① A jittery mapping trajectory was obtained by LIO-SAM

② Degeneracy occurred when MRP traveled back and turned to a new long aisle

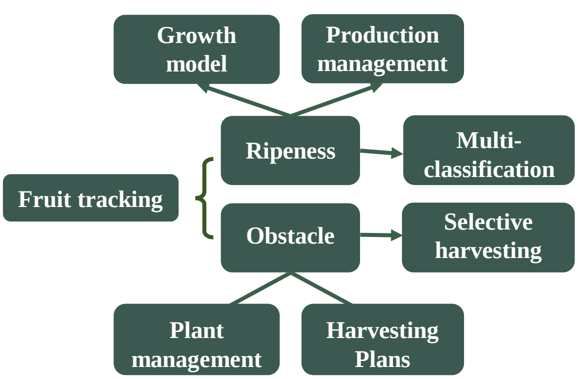
3) Localization

Positioning accuracy = 13.0 mm



Strawberry fruit sensing/detection

Motivation



Different fruits on a plant are at different stages of ripeness

Different fruits have different visibility

Strawberry fruit sensing/detection

Experiments

1) Total number of frames

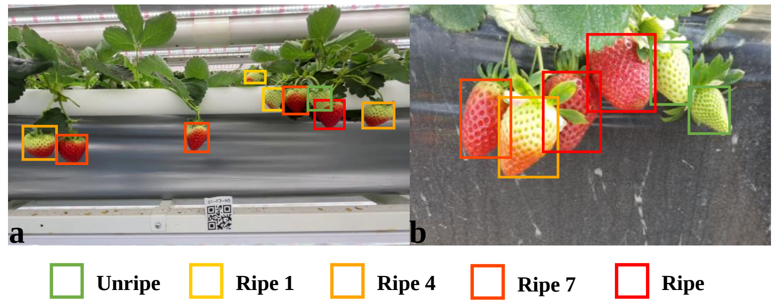
4D Bios (1426) + StrawDI_Db1 (174) = 1600

2) Total number of fruit in each category

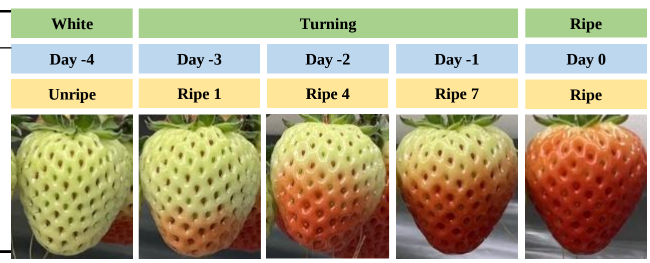
Unripe (3542)、Ripe 1 (421)、Ripe 4 (578)

Ripe 7 (1211)、Ripe (1142)

3) Results (using object detection algorithm YOLO model)

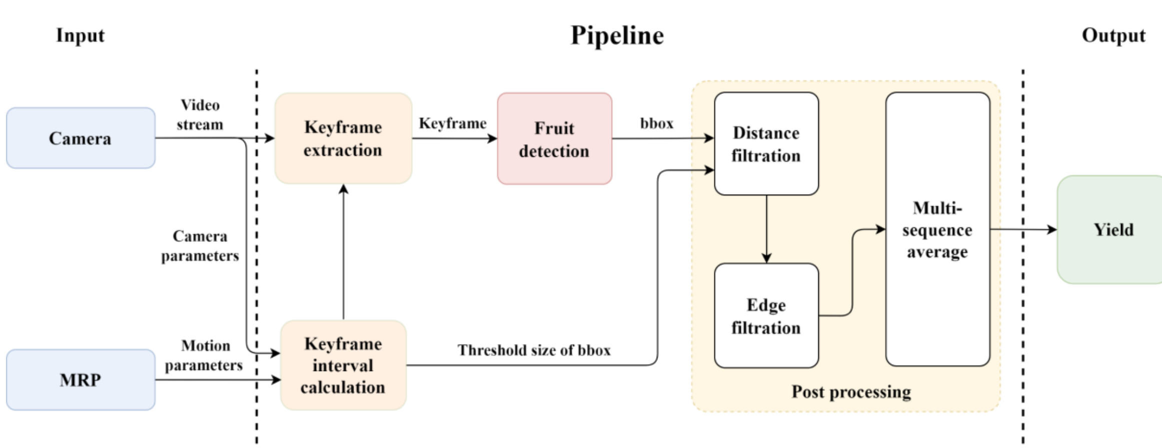


Classes	Labels	P	R	AP@0.5
Ripe	156	0.873	0.859	0.870
Ripe7	161	0.833	0.865	0.893
Ripe4	67	0.734	0.806	0.835
Ripe1	50	0.758	0.82	0.782
Unripe	496	0.875	0.864	0.896
All	930	0.815	0.843	0.855



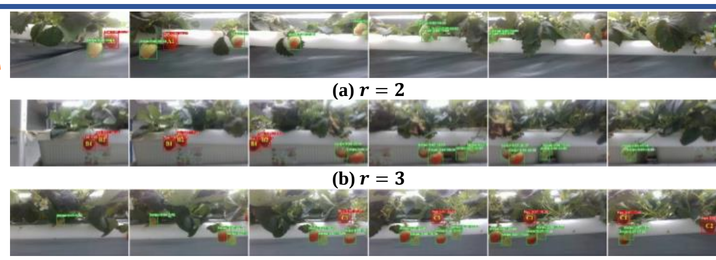
Strawberry yield monitoring

Pipeline



Strawberry yield monitoring

Counting-from-video problem



(a) $r = 2$

(b) $r = 3$

(c) $r = 4$

Example series of keyframes at various values of r.

1) Motivation

To determine the frame interval between keyframes (i) by fixing the number of counts for the same fruit (r)

2) Formulation

① Pixel distance of two neighboring keyframes (d_p) → Movement of MRP

② Assuming the speed of MRP (v), average distance between camera and fruit (d), frame rate of video (fps) to be constant

③ To calculate the theoretical interval of keyframes (i_t), take the nearest integer of i_t as the actual interval of keyframes (i)

w was the image width

f_x was camera's intrinsic parameter

$$d_p = \frac{w}{r}$$

$$i_t = \frac{d_p \times d \times fps}{f_x \times v}$$

$$i = int(i_t) = int\left(\frac{w \times d \times fps}{f_x \times v \times r}\right) \longrightarrow i = g(v \times r)$$

Statistics of fruit detection results of keyframes

Strawberry yield monitoring

Experiments

1) Goal

Yield monitoring accuracy under different speeds of MRP

2) Counting (i.e. monitoring) error rate

err^C: 2% ~ 3%

3) Yield (i.e. detection + monitoring) error rate

err^Y: 6% ~ 10%

e was the absolute difference between i and i_t

T was the tier number of growing unit

Setup				Video	n				$Avg\ err^C$	$Avg\ err^Y$
v (m/s)	**r**	**i**	**e**	**ID**	T1	T2	T3	T4		
0.2	15	3	0.044	1	34	52	87	70	0.0265	0.0626
	9	5	0.073	2	35	55	88	69		
0.3	15	2	0.029	1	37	54	88	71	0.0229	0.0905
	10	3	0.044							
	6	5	0.073	2	36	53	90	72		
0.4	11	2	0.075	1	37	51	85	71	0.0252	0.0711
	6	4	0.195	2	38	52	84	70		
	n_{GT}^C				36	54	85	70		
	n_{GT}^Y				32	51	83	65		

Mobile robotic strawberry monitoring

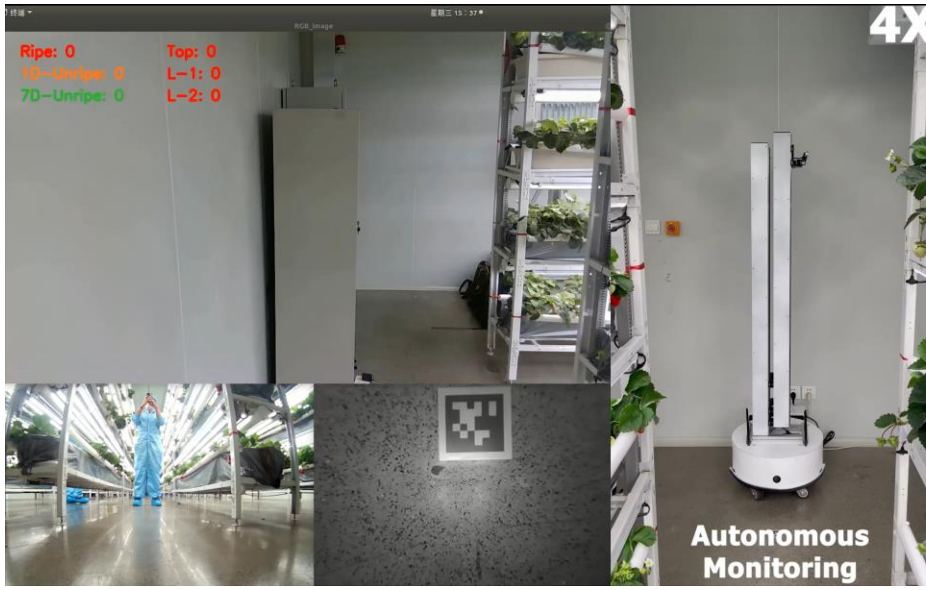
Demo

1) To collect standard data
2) To make intelligent decision

⇩

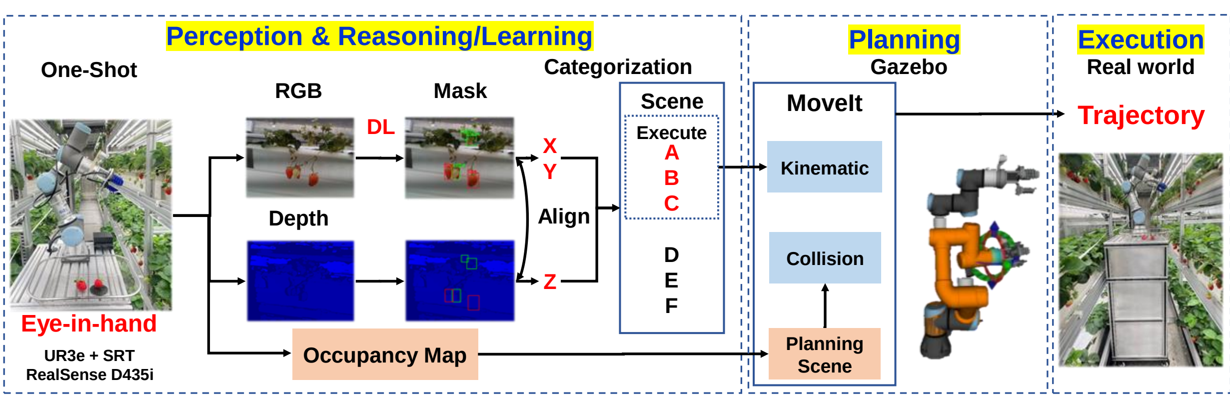
3) To replace manual operations

Data-driven Intelligent farms



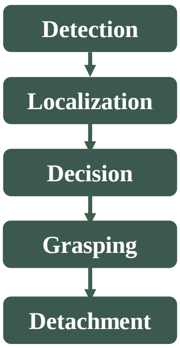
Strawberry fruit harvesting

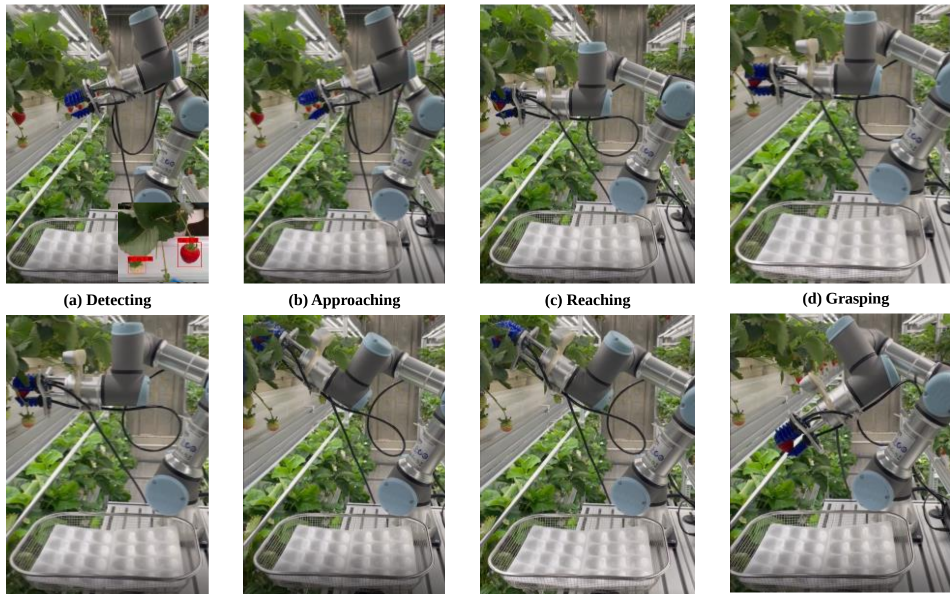
Robotic strawberry harvesting pipeline (See-Think-Act)



Strawberry fruit harvesting

Entire actions





(a) Detecting (b) Approaching (c) Reaching (d) Grasping

(e) Dragging (f) Rotating (g) Backing (h) Placing

Strawberry fruit harvesting

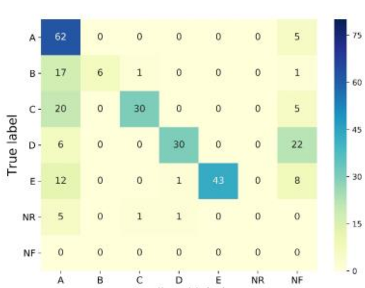
Rule-based approach to strawberry scene categorization for performing executable harvesting actions

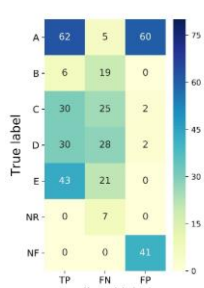
❑ Dataset

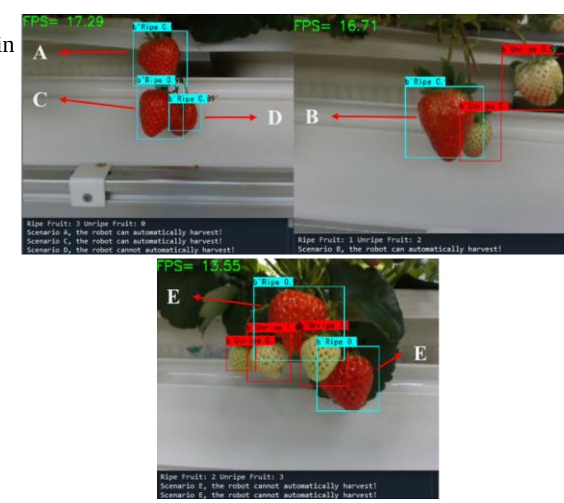
- The fruit growth scene categorization test set included **160** images in the strawberry ripeness test set, with 269 ripe and 213 unripe ones.
- A: 67, B: 25, C: 55, D: 58, E: 64

❑ Conclusion

For all, Accuracy = 89.1% Micro F1-score = 0.7
For scenario E, Accuracy = 92.4% Micro F1-score = 0.8







Samples of fruit growth scene categorization results

Strawberry fruit harvesting

Novel fruit detachment motions carried out by a soft end-effector, inspired by manual harvesting

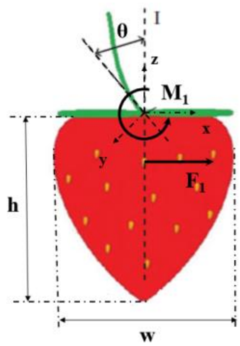
❑ *Improvements*

✓ Novel **fruit growth scene understanding**

Heuristic approach to **reduce unreachable attempts**

✓ **Non-destructive harvesting without stem**

Novel approach to gently separate the fruit from peduncle



Detachment approach – **Drag and Rotate**

(a) Real world (b) Simulation

Successful cases (Category A)

Strawberry fruit harvesting

Results

❑ *Success rate*

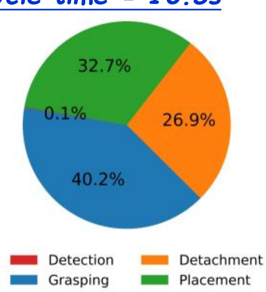
- For all

Success rate = 78%

- For scenario A

Success rate = 88%

❑ *Cycle time = 10.5s*



❑ *Failure case*

① Fruit B was mistakenly detected as Fruit A, causing detachment to fail.

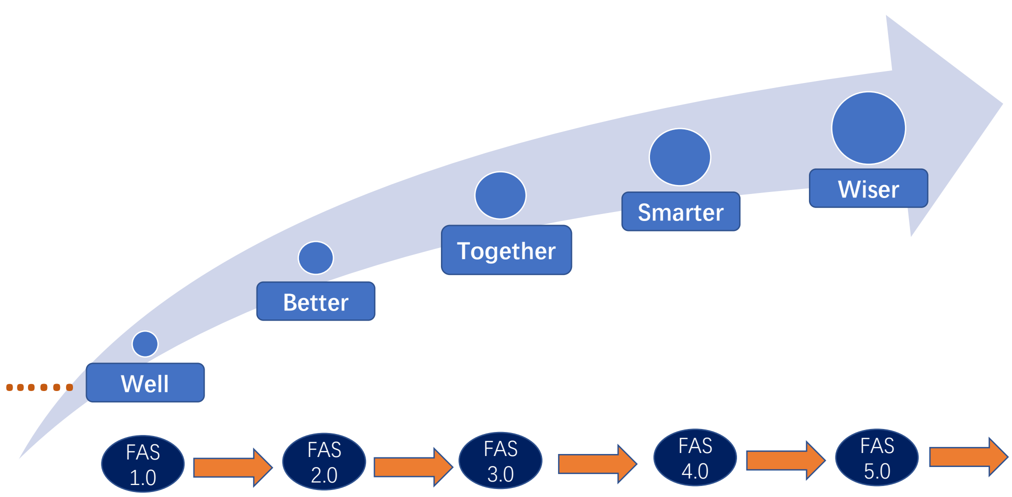
② Fruits C and D were mistakenly detected as A, causing localization to fail.

③ When harvesting Fruit C, Fruit D (A) was affected to fail in grasping and detachment.

Scenarios	Amount	Detection		Grasping		Detachment		Placement	Overall		
		S /%	T /ms	S /%	T /s	S /%	T /s	T /s	S /%	D /%	T /s
A	52	98	96	96	4.2	88	2.8	3.4	88	23	10.5
B	16	94	99	88	4.1	63	2.8	3.4	63	25	10.5
C	18	94	98	89	4.1	72	2.8	3.4	72	22	10.4
D	14	93	96	93	4.1	64	2.8	3.4	64	21	10.4
All	100	96	97	94	4.2	78	2.8	3.4	78	23	10.5

Demo

Concluding remarks - Make food and agriculture systems (FAS) work ......



Concluding remarks

❑ Work better

- **Heuristic approach** for fruit **scene categorization** to perform **executable** harvesting actions [TRL 3 to TRL 7]
- **Novel detachment approach** in end-effector motion plan **learnt from observation** [TRL 3 to TRL 7]
- Soft robotics, emphasizing **end-effectors** [TRL 4 to TRL 7]

❑ Work together

MRP has the abilities to **inspect** and **harvest** strawberry within **PIFS**

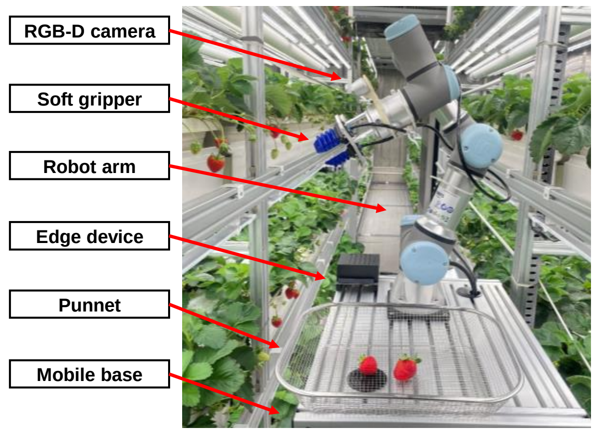
❑ Work smarter

Optimizing tasks both on the facility-wide **production strategy** and individual fruit **harvesting motion plan**

❑ Work Wiser – A long term goal

TRL - Technology readiness level

Hardware



Concluding remarks – *ACESys Model*

ACESys model:

Automation,
Culture,
Environment,
and Systems

Concluding remarks – Transforming food & agriculture systems of systems

convergence of multidisciplinary expertise and work

Things to be considered:

- ❑ Need a clear and well-communicated mission
- ❑ Define multiple objectives and consider trade-offs
- ❑ Understand complex constraints
- ❑ Be mindful of the involvement of multiple agents with different decision rules and behaviors
- ❑ Familiar with various types of constituent systems within an SoS, i.e. directed, acknowledged, collaborative, and virtual.
- ❑ Design mechanisms for measurement, analysis, actionable insights (including workable and optimum solutions), actions, continuous improvement (involving evaluation, feedforward, and feedback), etc.
- ❑ Involve multiple economic, professional, and governance sectors
- ❑ Develop and inform mapping among individual actions and overall mission goals
- ❑ Consider the question of who would benefit
- ❑ Work on the issue of inclusiveness and equity
- ❑ ……………………..

Thank you!

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