SpECULARIA

Structured Ecological CULtivation with Autonomous Robots in Indoor Agriculture

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***Abstract*— A robotic system to be used in small indoor organic farming is presented in this paper. The system consists of heterogenous robot agents with specific abilities, able to execute certain tasks only when working together, namely, an unmanned aerial robots (UAV), unmanned ground robots (UGV), and a compliant multi degree of freedom dual arm manipulator. The compliant manipulator, responsible for a delicate task of plant treatment, is developed within the Soft robotics paradigm. Using the Soft robotics principles, a dexterous human like motion can be achieved through simultaneous deployment of soft robot body parts, compliant control, and tactile sensing capabilities of the manipulator. Testing the robots on the described challenging application represents an interesting research opportunity that will certainly lead to new results in the rapidly expanding field of research that soft robotics represents.**

I. Introduction

In the first century CE, two Roman agricultural writers, Lucius Junius Moderatus Columella and Gaius Plinius Secundus (Pliny the Elder), referred to proto-greenhouses (specularia) constructed for the Emperor Tiberius (42 BCE–37 CE), presumably adjacent to his palace, the Villa Jovis on the Isle of Capri. Pliny wrote (Book 19, 23: 64) that the specularia consisted of beds mounted on wheels which they moved out into the sun and then on wintry days withdrew under the cover of frames glazed with transparent stone [1].

This hundreds of years old idea is still applicable today, if not even more so. In the world that is suffering for ever more obvious pollution consequences, organic farming represents a step towards reducing the pollution with an environment friendly solution. Unfortunately, in order to reduce the use of pesticides and GMO cultures, organic agriculture becomes ever more labour intensive, with a comparably smaller agricultural output. The obvious economical consequence of such a production system is a higher cost of organic food. The labor input in organic agriculture fits the description of dull and dangerous jobs, and therefore ideally fits the use of robots.

Deployment of robots on big farms is not a new concept, but rather a fast growing industry that focuses on big machines applied for specific crops and use cases.

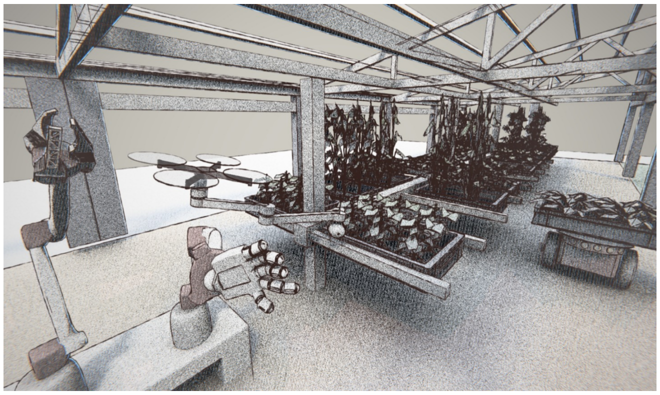

Fig. 1: Heterogeneous robotic system in a Specularia of 21st century

II. System Overview

The proposed system, inspired by the antic specularia is shown in Fig. 1. It goes beyond current state of the art, in a sense that it proposes a system comprised of small robots with specific abilities that can execute certain tasks only when they are introduced to work together. Such a system surpasses current farming robots in its scalability and versatility, which makes it ideal for small family run organic farms.

We envision a team of robots comprised of three types of agents:

- The Unmanned Aerial Vehicle (UAV) is equipped with a multi degree of freedom manipulator carrying sensors for plant surveillance.
- The Unmanned Ground Vehicle (UGV) is equipped with a mechanism allowing it to transport growth unit containers.
- The multi degree of freedom (DoF) manipulator is utilized to perform delicate handling of plants.

A primary goal of this heterogeneous robotic system is to optimize light distribution for photosynthesis, gas exchange, carbon allocation, and ideally bring the fruit to the exact position for the harvest. We aim to use Functional-structural plant models (FSPM) as a tool to plan plant treatment [2]. More specifically, a series of treatment tasks will be planned and conducted based on the results of comparison of the desired 3D representation of the plant (FSPM) and actual configuration (3D model).

The manipulator plays a crucial role in this task, being

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responsible for operations like physical flower and fruit manipulation, plant pruning, and other plant hygiene operations, as well as other mechanical interventions at the plant's structure. In realizing this deployment scenario for the manipulator, dexterous human like motion will have to be achieved based on Soft robotics control, construction, and sensing principles.

One example scenario of manipulator deployment would include the following steps:

1) The manipulator creates a LIDAR 3D scan of the plant.
2) The compliant manipulator equipped with soft bodied tactile sensors explores the plant body. The tactile exploration is planned locally based on the local plant curvature in 3D space, estimated from the local contact force distribution over the force sensors array.
3) The PointCloud plant model constructed from the 3D scan and tactile exploration is compared to the FSPM, and required treatment operations are identified.
4) The mission planner controls task execution over an inner force (impedance) control loop of the manipulator. The force control loop ensures a stable but gentle grip on the plant parts, preventing harmful actions.
5) Contact force information during manipulation is used for mission planner adaptation.
6) A new plant model is constructed, and the procedure is repeated until the plant model matches the FSPM.

III. SOFT ROBOTICS PRINCIPLES

When considering treating sensitive plants, soft systems surpass rigid robots in grasping and manipulating unknown plant shapes even with straightforward control schemes. As described in section II, an important agent in the proposed system is a manipulator built using the three key enablers of Soft robot technology: soft materials, sensing and compliant control algorithms [3]. The system is imagined to consist of a dual arm manipulator, where both robot arms are traditional rigid manipulators, one equipped with soft bodied grippers, and the other with soft sensing apparatus providing feedback for compliant robot control. This ensures that the robot can execute given manipulation tasks, and at the same time make sure that the plant is not harmed.

A. Construction

Soft bodied robots promise to move with the ability to bend and twist, and can thus be used in confined spaces [4]. The ability to adapt their shape to the environment together with compliant motion [5] makes them ideal for a variety of applications, such as medical and wearable applications. The envisioned scenario offers a unique environment to further develop the potential of soft robots.

In the proposed use case, soft bodied under-actuated grippers will be utilized, relying on commercially developed flexible grippers. Such grippers, composed of silicone elastomers with embedded pneumatic channels have demonstrated impressive adaptability [6]. The control of such under-actuated soft gripper will be enabled using the developed static, dynamic and kinematic models, capturing the ability of the body to bend and flex [7].

The arm of the dual arm manipulator equipped with these grippers will be used for plant stabilization during manipulation. While the force sensing and controlled arm conducts the treating procedure, this, position controlled arm, holds the plant body in place, allowing for small imprecisions and displacements through the soft bodied structure of its grippers.

B. Compliant control

One of the key research topics project aims to address is compliant manipulator control. Typical robotic tasks that require interaction with the environment dictate that the contact forces must properly be handled by the robot controller [8]. In a task dealing with sensitive and delicate environment, such as plants, this issue is resolved through compliant control of the employed manipulator.

Compliance can be introduced in the robot behavior using a linear second-order impedance filter given with eq. 1. Using the mathematical model of the system derived from rigid body kinematics and Newton-Euler dynamics analysis, the filter allows indirect contact force control through end-effector position control, assuming known (and constant) position x_e and equivalent stiffness k_e of the environment.

$$\mathbf{e} = M\ddot{\mathbf{x}}_c + B\dot{\mathbf{x}}_c + K(\mathbf{x}_c - \mathbf{x}_r). \tag{1}$$

The force error signal, $e = f_r - f_m$, adjusts the actual commanded position reference x_c in relation to the user specified position reference x_r, in a force error minimising direction following the second order dynamics defined by fixed filter parameters M, B, and K. However, since the measured force $f_m = k_e(x_c - x_e)$ represents the response of the environment, the uncertainties of the environment position and mechanical properties, in most use cases, including the one proposed here, result in a steady state error in force tracking (eq. 2), as shown in [9]. This, along with the nonlinearity introduced by soft end-effector gripper, will have to be taken into account in adaptation of existing control solutions.

$$e_{ss} = \frac{k}{k + k_e}[(f_r + k_e x_e) - k_e x_r]. \tag{2}$$

One of the adaptations to be deployed is introduction of model adaptive control of the position reference x_r, based on the deviation of the force error signal from a chosen error model, as described in [9]. Additionally, as one of the main outputs of the proposed research, a hierarchical mission (trajectory) planner will be developed.

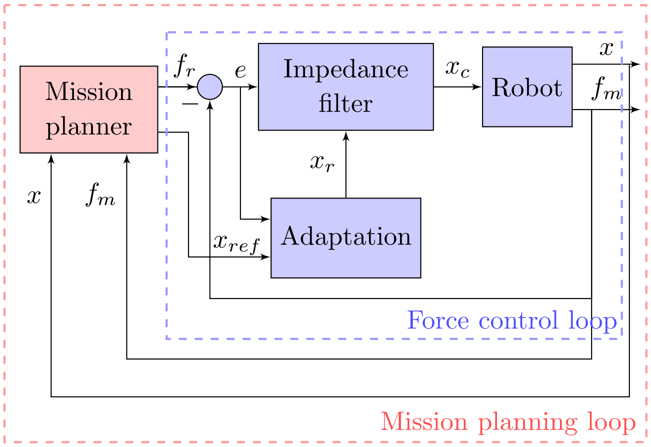

Fig. 2: Control of the manipulator. Inner force control loop relies on the impedance control approach, adapting the position reference based on the force error signal. The outer loop generates task related force references and trajectories under various constraints.

The primary task of the planner is the end-effector contact force reference and trajectory generation, based on the expert definition of plant treatment procedures. The secondary task is to position the adaptive envelope of the whole robot in relation to the environment [4].

The overall system control loop schematic, shown in Fig. 2, shows the relation of the inner force control loop (impedance control), and the higher level mission planning control. The trajectories of the planner's primary task are referenced into the system along with the constraints introduced within the secondary task. The schematic does not show the inner joint control loop within the *ROBOT* block, nor the dynamics of the force measuring apparatus.

C. Sensing

In order to enable the compliant control of a traditional position controlled robot manipulator, a feedback information on contact force is needed. In terms of soft robotics, tactile sensing feedback is considered essential for complex precise manipulation tasks as well as for safe interaction with the environment [10]. Different technologies are employed in trying to develop a sensor that adequately balances the quality and usability of acquired information with the compliant mechanical structure of the sensor body that satisfies safety requirements of robot interaction with the fragile envinronment [11].

In the envisioned scenario, the force controlled manipulator arm end effector will be equipped with soft bodied optical based force sensors, such as one from the TacTip family of bioinspired optical sensors developed by Bristol Robotics Laboratory [10]. The sensor consists of a hemispherical (black) silicone tip filled with a silicone gel, and a camera directed towards the interior of the tip. Inspired by the Merkel Cell complex in human skin, the inside of the hemisphere contains a pattern of white-tipped pins, used to conduct and amplify the movement of the outer tip membrane while in contact with the environment [16]. Adequate processing of the pin movement can provide spatial information and force measurements.

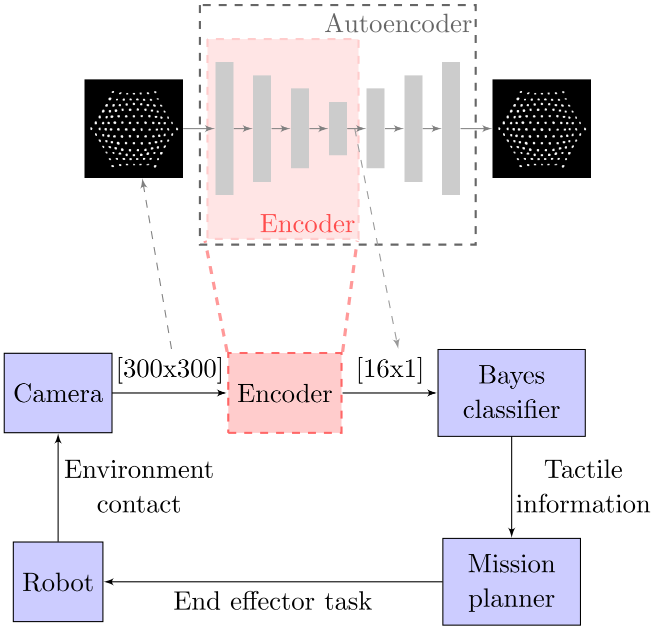

Fig. 3: Robot control loop with emphasis on the feedback information generation. The TacTip optical sensor captures tactile information in the form of a camera image. The image is transformed into a low-dimensional set of features using a convolutional encoder network. Machine learning models trained for different applications (e.g. spatial information classifier) are used for tactile information extraction, and fed into the control algorithms.

A Bayesian perception algorithm applied to a subset of pin coordinates in the TacTip sensor output has been successfully applied in extracting spatial information about the contact [12]. Similar results have been obtained using a different set of features: instead of deterministic image feature tracking algorithm, a convolutional neural network encoder was used for feature extraction. This online feature extraction method maps the problem into an orthogonal feature space of a lower dimensionality, eliminating the complex mathematical model of pin displacement in the image processing algorithm.

A Bayesian perceptron applied to this set of features managed to replicate the accuracy of the results presented in [12]. A similar approach is to be applied in extracting local contact force information, which can then be used as a feedback signal in the control loop as shown in fig.3.

Additionally, the force and spatial contact information will be used in building a PointCloud structure, which will enable creating a plant model. In combination with a FSPM plant model, this structure will be used by the mission planner in deciding on required plant treatment actions.

Since an array of sensors is used, both through an end effector gripper, and among the fingers, it is expected that an optimal sensor distribution can be found in terms of trajectory planning and force control quality. Additionally, the soft deformable structure of the sensor surface will ensure interaction safe from unintentional harm to the plant body.

IV. Conclusion

The described project is expected to yield a trajectory planning platform based on 3D scan input and FSPM comparison, developed under the Soft robotics paradigm. Based on the results of comparison of the desired 3D representation of the plant (FSPM) and actual configuration (3D scan), the platform will plan a series of treatment tasks that need to be executed to match the 3D scan with FSPM. It is easy to imagine that the dual arm manipulation system must plan to grasp and re-grasp the 3D scanner, to first build a 3D representation of the plant, and then to verify that the manipulation task has achieved the desired goal. In the meantime, the system must lay down the scanner to be able to treat the plant. Throughout the execution, the changing envelope of the whole robot in relation to the environment will have to be considered in order to prevent harmful contact with the plant body.

To execute the motion, the arms of the dual arm manipulator must be enabled with soft sensing and compliant control end effector capabilities, and soft bodied grasping end effector, respectively. The deployment of existing technologies, as well as parallel development of new algorithms in sensing and control, are expected to yield new insights in Soft robotics approach, enabling further advancements and applications, both in agriculture, and in other fields requiring high precision manipulation.

V. Acknowledgment

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