# DATE: A Handheld Co-Robotic Device for Automated Tuning of Emitters to Enable Precision Irrigation

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***Abstract*— Agriculture accounts for 85% of the world's freshwater usage. Drip irrigation significantly reduces water usage and has been adopted by many farms, orchards, and vineyards. Rubber or PVC tubing is fitted with thousands of drip emitters whose water pressure and flow are controlled by a small number of valves resulting in suboptimal use of water resources. While UAVs and other sensors can be used to determine water needs and compute appropriate emitter settings, it is currently not possible to close the loop: adjusting flow at the individual plant level to compensate for variations in plant and soil properties, elevation, sun-angle, evapotranspiration, drainage, and emitter contamination by dirt or insects. We propose retro-fitting existing systems with low-cost, passive, plastic, screw-adjustable emitters that are commercially available. This paper presents a design for an automated device that would allow passive emitters to be systematically adjusted in the field by human and robot teams to fine-tune water delivery at the plant level. This paper describes the mechatronic design, prototype, and initial experiments with a hand-held version of the device with a coarse-to-fine mechanism to facilitate alignment to passive emitters in the field and precise automated adjustment of flow settings. We report experiments with an implemented prototype that can compensate for orientation error up to $\pm 39$ degrees and position error up to $\pm 42.5$mm when adjusting a $16$mm emitter cap.**

## I. Introduction

Agricultural irrigation consumes 85% of the world's freshwater [11]. As global human populations continue to grow, increasing demand for irrigation water strains water supplies limited by drought and variability due to climate change [35]. As a result of sustained drought in California, the Central Valley agricultural region's water availability in 2015 was at 48% of average levels resulting in a total economic impact of $2.7 billion and a loss of 21,000 jobs [16]. Restrictions in water use motivate efficient drip irrigation techniques [21].

Several studies have been made comparing sub-surface, surface, and furrow drip irrigation methods. Sub-surface drip irrigation is slightly more water efficient but less cost efficient than exposed furrow irrigation [13]. Furrow drip irrigation is a widely adopted irrigation technique which uses arrays of pipes to deliver water from a source to thousands of drip emitters in parallel mounted on irrigation lines 18 inches above the soil surface (shown in Figure 2b). Furrow drip irrigation is less prone to clogging and easier to maintain and adapt than surface or sub-surface drip irrigation. Water outputs for all types of drip irrigation are actuated for blocks of hundreds of emitters at once. Ideally, each plant should be individually monitored and maintained to maximize yield and quality while minimizing water consumption.


Fig. 1: The Device for Automatic Tuning of Emitters (DATE) can guide workers though fields to adjust passive irrigation emitters. The DATE features a novel two-stage manipulator that cages co-designed adjustable emitters (shown in inset). The handheld DATE and a scaled-down version for robotic manipulators can enable human-robot teams to control irrigation levels at the plant level.

Insufficient irrigation adversely effects plant physiology and crop yield; if prolonged, this condition is known as *water stress* [24]. In the case of wine grapes (grown throughout California, including the Central Valley) it is desirable to selectively stress each vine to maintain a desired concen-

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tration of sugars and development of flavinoids. Precision viticulture is an emerging area with increasing impact in the wine-growing sector [4] and similar plant-level irrigation is desired for other high value crops such as almonds [19].

Technologies such as Unmanned Aerial Vehicles (UAVs) equipped with heterogeneous sensors can provide farmers with detailed maps of water use and ground conditions. Soil moisture probes can also be used to track local water properties in the field. However, closing the sensing-actuation loop to adjust irrigation at the plant level remains an unsolved challenge.

***Contributions:*** We present the design of a handheld Device for Automated Tuning of Emitters (DATE) for actuation of a precision irrigation system. We present a novel design for a two-stage mechanical gripper that automatically aligns to and adjusts individual emitter output. We prototype the DATE as a handheld device (illustrated in Figure 1) which can guide workers (robotic or human) through a field to locate the next emitter to be adjusted. We also provide experimental evaluation of the DATE's ability to dock and adjust emitters under position and orientation uncertainty.

## II. Related Work

**Sensing and Modeling for Precision Irrigation:** The effectiveness of precision irrigation systems relies on the ability to sense and predict plant water stress or soil moisture. The problem of spatially varying moisture measurement and simulation has been extensively studied [28] using models based on finite differences, nonlinear differential equations and partial differential equations. Temporal variability has been considered in [34]. Methods specifically aiming at modeling subsurface moisture with drip irrigation have been developed and experimentally validated [18]. Building upon these models, several simulation packages are available for modeling surface, subsurface, and groundwater flow. Software packages like HYDRUS 2D/3D [2] have been used for modeling flow and designing drip irrigation systems [25]. However, once these systems are in place there is no commercially viable method for actuating water output levels on a per-plant basis.

Different sensing modalities for estimating plant water availability across vineyards has received a lot of attention, and there is a rich history regarding soil moisture measurement techniques [26]. Recently, airborne thermal imagery has been used to assess the spatial variability of water stress, an indicator of soil moisture availability, across vineyards [8], as well as soil moisture probes based on soil electroconductivity. Wireless sensor networks (WSN) have been proposed for environmental monitoring and applications in agriculture [33].

A WSN composed of 135 soil moisture and 27 temperature sensors was deployed in an apple tree orchard of about 5000 $m^2$ [22]. The network is in charge of estimating soil moisture, but does not include an actuation subsystem capable of adjusting the application of water. A similar system was proposed in [23] where it was demonstrated that current sensing technology is mature to determine soil moisture levels.

**Automated Irrigation Systems:** Information regarding soil moisture level and evapotranspiration can be obtained using soil probes, near infrared (NIR) cameras, thermal sensors mounted on robots, UAV's, weather information, satellite imagery, or online services like the California Irrigation Management Information System (CIMIS) [1]. Although such information can be used to inform irrigation plans, irrigation control is still accomplished commercially at the (coarse) block level [12].

Another approach to achieving fine control of irrigation is the deployment of an actuated emitter at each plant. However, installing thousands of actuated emitters in the field poses technical challenges as well as economic ones. There is a risk of degradation due to enironmental conditions and pests such as the Northern Pocket Gopher *(Geomys bursarius)* [30], and costs associated with individual actuated irrigation nodes scale prohibitively over large-scale farming operations. A detailed economic analysis of a 10-node wireless sensor and actuator system for precision irrigation can be found in [9]. The success of a precision irrigation system is contingent upon keeping distributed emitter and equipment costs low.

**Mobile Robotic Platforms in Agriculture:** Autonomous robotic systems are becoming an integral component in agricultural operations [6]. Distributed systems of UGVs operating autonomously, for example fleets of autonomous tractors for harvesting [17] have been explored as solutions to labor shortages in agricultural settings [36]. Following the commercialization of computer vision sensors, global positioning systems, LIDAR, and Inertial Measurement Units (IMUs), robotics research over the past two decades has led to many examples of unmanned robotic vehicles and service units in agriculture [10]. Several demonstrated uses of UGVs in agriculture include weed detection [7] and precision herbicide deployment [31].

**Grasp Planning under Uncertainty:** The UGV with the DATE mounted on a robotic arm will travel through an outdoor agricultural environment with large variability in textures and scenic clutter. Recent work [29] proposed heuristics to grasp unknown or unrecognized objects based on both the overall shape of the object and local features obtained from RGB-D sensor data. Active exploration using an eye-in-hand range sensor has been used for 3D scene reconstruction [32] and object detection in cluttered environments [5]. Active exploration for robotic grasping has been explored in prior work [15]. Methods for grasping unknown objects [3] use active exploration to reconstruct the 3D geometry of the object before planning a grasp.

Research on caging grasps, where an object's mobility is constrained to not move arbitrarily far away from the manipulator instead of immobilizing the object completely, has recently shown promise for manipulation tasks, since caging grasps allow increased flexibility compared to classical force closure grasps [20]. The connection between caging and grasping has also been investigated in [27], which showed that increasingly tight cages can result in force


(a) Fixed-flow emitter Diameter 0.75in

(b) Fixed-flow emitter mounted in 1in diameter drip irrigation line

(c) Adjustable Flow emitter diameter 0.6in

Fig. 2: Fixed-flow drip irrigation emitters are commonly employed in fields. Adjustable emitters (Figure 2c) allow variations in water drip rate but are not yet used in commercial growing operations because they are tedious to tune by hand in large quantities.

closure grasps. The closing mechanism of our design also incorporates aspects of this philosophy, since the drip valve is being increasingly constrained as our mechanism closes.

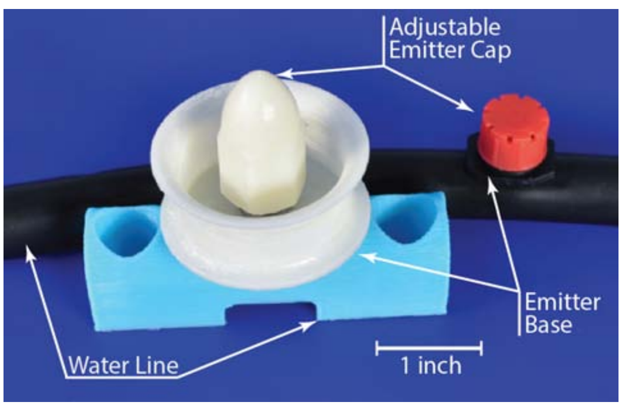


Fig. 3: The adjustable emitter (shown at left) redesigned to interface with the DATE. A commercially available design is shown at right mounted on 0.75in PVC irrigation line. The 45mm collar surrounding the redesigned (white) emitter is designed to aid in grasping.

## III. System Design

The DATE is designed with the following constraints:

1. Positive engagement between the gripper and the emitter,
2. Modularity for mounting to a human-interface grip or robotic arm,
3. Ability to overcome positional uncertainty between the DATE and the emitter,
4. Individual emitter locating within a field of thousands spaced 1m, and
5. Remote base station communication to update control parameters.

### A. Emitter Design

The emitter is the distributed, passive component in the precision irrigation network. With thousands of units in the field, each emitter must be inexpensive (less than $0.30) for precision irrigation to be viable. The adjustable emitter design presented is based on the emitter shown in Figure 2c. A collar feature has been added to the base of the emitter to engage with the coarse mechanical manipulators (shown in Figure 5) and allow for caging of the emitter. The cap of the emitter has been designed to include features to allow for adjustment of water flow ($0 - 10$ gallons per hour) through rotation of the cap with respect to the base of the emitter. Hex indexing features are built into both the cap and gripper for engagement by the fine manipulator as seen in Figure 1.

### B. DATE Design

The gripper of the DATE consists of two mechanical manipulation stages designed to positively engage an adjustable emitter while passively overcoming positional uncertainty. The DATE also includes a 1300mAh lithium-ion battery and sensors and electronics used to both communicate with a base station and guide the user through the field.

**Coarse Mechanical Manipulator:** The first manipulation stage orients the DATE with respect to the emitter base. The coarse mechanical manipulator uses two rotating arms (shown in Figure 5) each powered by Actobotics Planetary Gear Motors (638288) with optical encoders to center the emitter within the capture region of the DATE. The rotating arms act as a mechanical iris to draw the center axis of the DATE in-line with the center axis of the emitter.

**Fine Mechanical Manipulator:** With the emitter centered the second stage fine mechanical manipulator is inserted to interface with the emitter cap. The fine mechanical manipulator is designed to funnel the cap of the emitter into engagement (see Figure 6). The fine mechanical manipulation stage is inserted by a servo (Futaba $S3003$). Torque is applied to the cap of the emitter using a Faulhaber $2342S012CR$ with optical encoders.

### C. Sensors and Electronics

An Arduino Mega (2560) 16MHz microprocessor controls the motors and sensors. Cloud connectivity is provided by a SIM808 GSM/GPRS+GPS Module. Position within the field is measured using a Mediatek MT3337 22 channel GPS, accurate to 2.5m. Communication to existing wireless sensor networks [14] is accomplished with an XBee series 2,

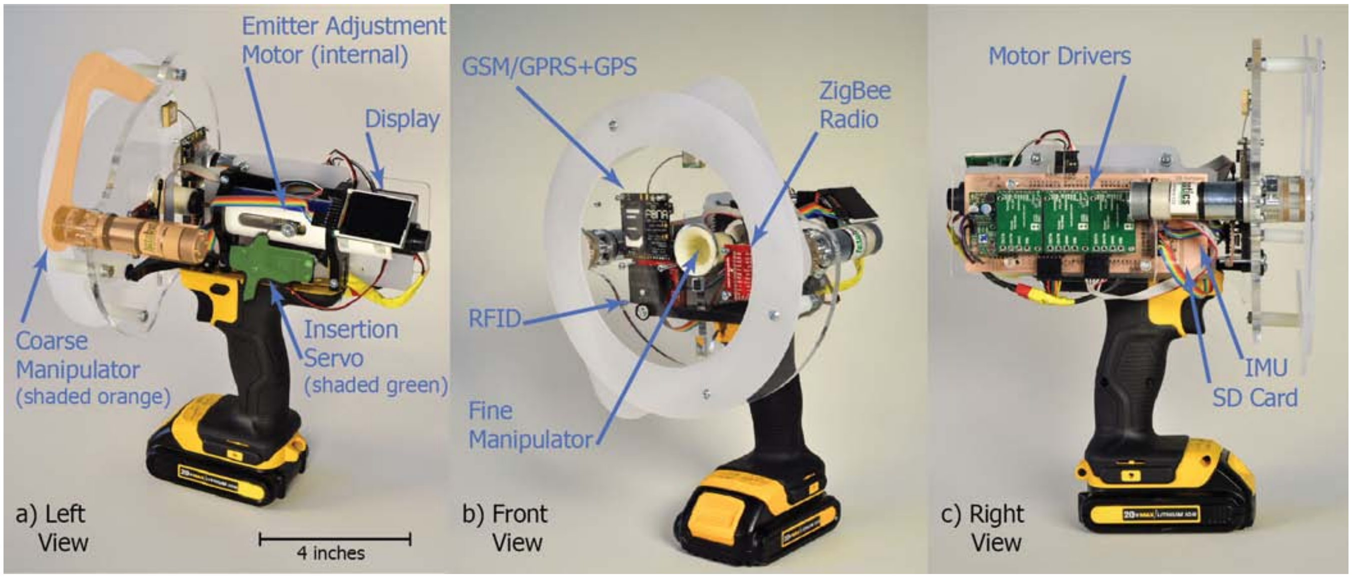


Fig. 4: The DATE in hand-held form houses the sensors required for a worker or UGV in the field to locate and adjust emitters.

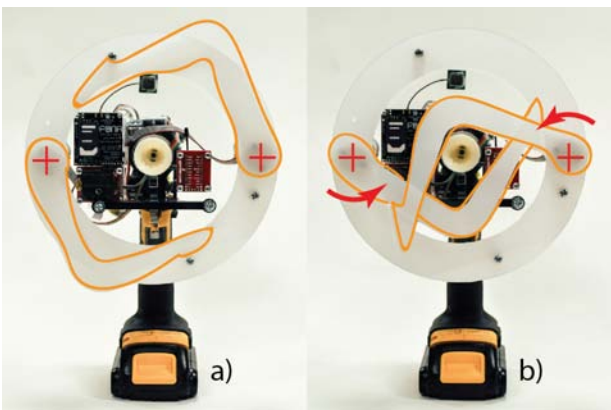


Fig. 5: The DATE is able to overcome positional misalignment by caging the emitter base between within its 1-DOF coarse gripper acting as a mechanical iris. The coarse manipulator fingers are outlined in orange; torque applied to center the DATE around the base of the emitter is illustrated in red. When the trigger is pulled, the fingers rotate from the position in Figure 5.a to the position in Figure 5.b.

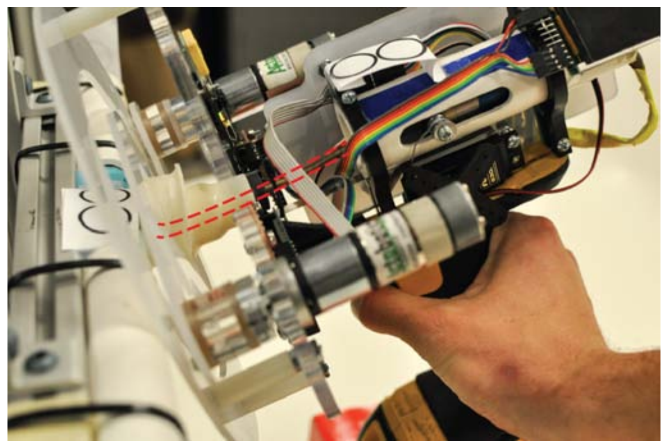

Fig. 6: After the base (collar) of the emitter has been caged, the fine mechanical manipulator inserts to engage the cap of the emitter. Torque to adjust the emitter cap is supplied through a flexible shaft (highlighted in red) that overcomes any remaining misalignment between the adjustable emitter and the DATE.

2mW wire antenna, ZigBee protocol radio (XB24-$Z$7WIT-004) with 5000ft line-of-sight communication range by Digi. An ID-12LA Radio Frequency IDentification (RFID) module by Innovations is used for short (<5cm range) emitter identification. When combined with the fact that a user will likely adjust patches of emitters, he short range RFID confirmation eliminates mismatch errors which can arise from false initial guesses between targeted and actual emitters grasped due to the lower resolution of GPS.

The RFID confirmation eliminates errors which could arise from lower resolution GPS. A LSM9DSO 9 Degree of Freedom (DOF) Inertial Measurement Unit (IMU) by ST Micro is used to determine the compass heading of the worker in the field for navigation between actuation points. An 8GB SD card is used for internal storage of database parameters and to store accumulated WSN data between uplinks to the base station. Power is supplied by a 20V 1300mAh lithium-ion battery.

## IV. Experimental Evaluation

An adjustable emitter was mounted to a section of irrigation line below a camera as seen in Figure 7. Lateral and angular offsets of the DATE were measured with respect to the tip of the emitter using template matching. This positional data was collected each time the trigger on the DATE was pulled, stored as an *approach vector*, and manually annotated with the success or failure of the DATE to deliver torque to the emitter cap. Lateral and angular offsets are handled separately by the coarse and fine actuation stages and thus separate data was collected for each stage.

Specifically we evaluate:

1. Coarse mechanical gripping to overcome lateral offsets
2. Fine mechanical gripping to overcome angular offsets
3. The resulting capture region

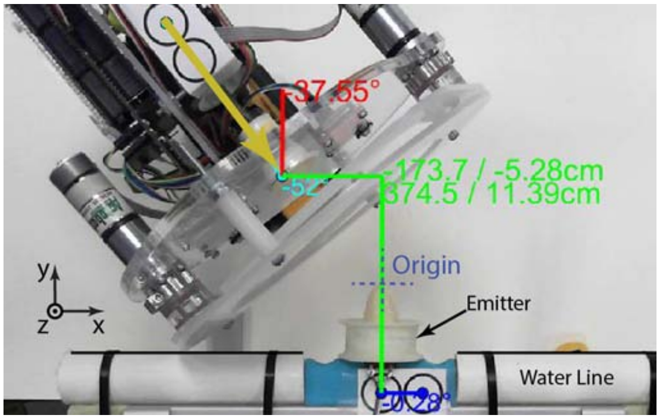


Fig. 7: A visual tracking system was used to record success and failure of grasping trials. Template matching was used to record the position of the DATE with respect to the origin (emitter tip). The yellow arrow represents the approach vector of the DATE to the emitter origin.

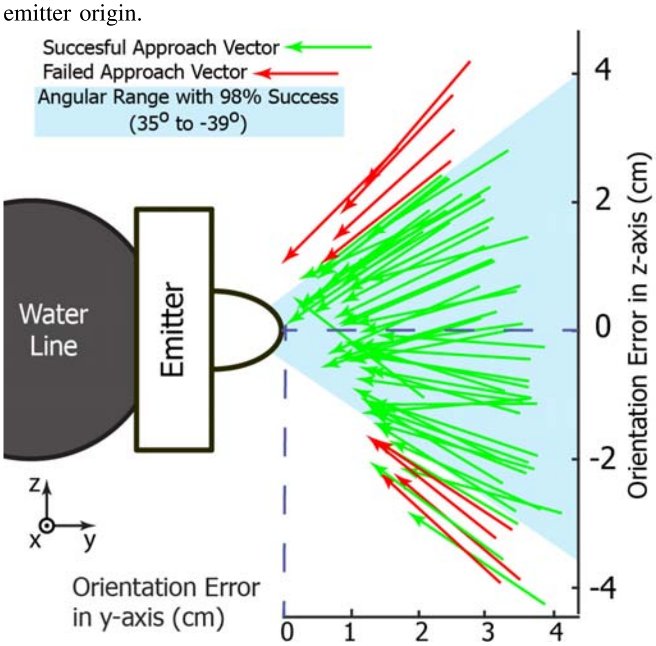


Fig. 8: The DATE's two-stage mechanical manipulators can overcome 74 degrees of angular uncertainty in interfacing with a 16mm diameter emitter cap in 98% of trials. Each arrow represents an approach vector from each grasping trial (see Figure 7) Green vectors represent successful gripper re-orientation and positive emitter grasp. Red vectors represent grasp failures.

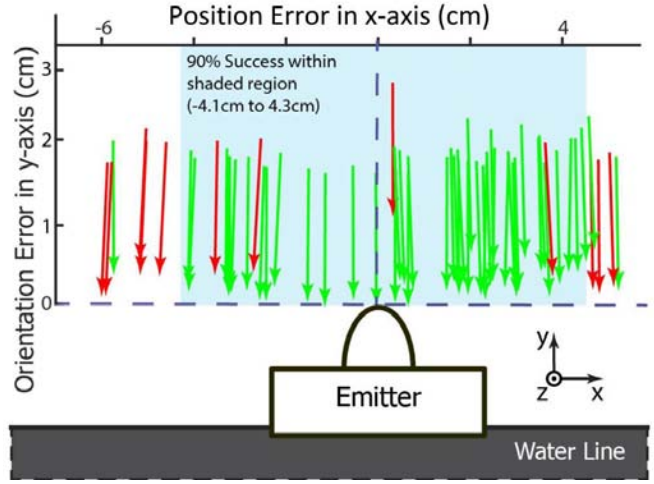


Fig. 9: The DATE can successfully grasp a 16mm diameter emitter cap despite an uncertainty range of 84mm in 90% of grasp attempts. Green vectors represent successful gripper re-orientation and positive emitter grasp. Red vectors represent grasp failures.

**Angular Uncertainty:** The extent of the angular capture region of the DATE was investigated using a side-mounted camera and a similar vision-based tracking system as described above. During this experiment, the DATE was constrained within the z-y plane (as described in Figure 7) and allowed to rotate freely about the x-axis. Success was measured as a positive rotational lock with the emitter cap. Figure 8 shows all 60 grasp trials. Grasping success quickly deteriorated above 39 degrees and below $-35$ degrees from horizontal (defined as the x-y plane as seen in Figure 7). The DATE had 98% success in grasping within this 74 degree area.

**Lateral Uncertainty:** The DATE was interfaced with an emitter in 60 trials of lateral position uncertainty (along the x-axis as described in Figure 7). During this experiment, the DATE was placed over the emitter with a consistent angle of approach about the z-axis. Position was limited to the area within the entrance ring of the DATE (shown in Figure 4.b). Success was measured as a positive rotational lock with the emitter cap. There was a 90% success rate within the region $-4.1$cm and 4.3cm from the emitter origin. Some failures were caused by insufficient insertion of the emitter base into the coarse mechanical manipulators of the DATE. Figure 9 describes the lateral extent of the DATE capture region. The DATE had 90% success in grasping the 45mm diameter emitter base over a window of 8.4cm ($-4.1$cm to 4.3cm from origin).

## V. Discussion and Future Work

The functional prototype presented in this paper represents the first step to determine the characteristics for a robotic- or human-centered gripper to interface with adjustable drip irrigation emitters distributed in an agricultural operation. We also considered the sensors and actuators requisite to enable a roving worker to automatically interface and adjust individual emitters as directed by a cloud-based control algorithm. The results of our experimental evaluation show that the mechanism can handle up to 4cm of lateral and 35 degrees of rotational misalignment.

**In future work:** The 60 grasping trials illustrated in Figure 9 were constrained to be orthogonal to the water line because the flat face plate of the DATE seen in Figure 7 collided before the emitter collar could reach the coarse manipulators. To address this angle of uncertainty, the DATE will be redesigned with a compliant faceplate.

In the current form, a human operator is required to coarsely position the system. After minimizing the overall size of the DATE, the gripper design presented here can also be mounted to the end of an UGV arm, e.g. the *Jackal* UGV by *Clearpath Robotics* which which can be interfaced with a 6DOF *Kinova MICO* arm. Future work will involve field evaluations of both human and robot-driven versions of the gripper, performed with farm managers and growers in the wine producing regions of California (Central Valley, Napa, Sonoma, and Mendocino Counties), as well as the task allocation algorithms that will support both platforms.

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