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. UAVs and other sensors are used to determine water needs and compute appropriate valve settings. As there are far more plants than valves, it is currently not possible to achieve "precision irrigation": 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. As it is possible to retro-fit existing systems with low-cost, passive plastic screw-adjustable emitters that are commercially available, this paper presents a design for an automated "co-robotic" device that would allow such emitters to be systematically adjusted in the field to fine-tune water delivery at the plant level. This paper describes the mechatronic design, prototype, and initial experiments with a hand-held device designed 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 ±39 degrees and position error up to ±42.5mm when adjusting a 16mm emitter cap.**

I. INTRODUCTION

Agricultural irrigation consumes 85% of the world's freshwater [27]. As global human populations continue to grow, increased demand for irrigation water puts strain on water supply already strained by prolonged drought and increased variability due to climate change [39, 51]. As a result of sustained drought in California, in 2015 the Central Valley agricultural region's water availability was 48% of historic levels resulting in a total economic impact of $2.7 billion and a loss of $21,000$ jobs [31]. Restrictions in water use motivate efficient drip irrigation techniques [4].

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).

Several studies have been made comparing the subsurface, surface, and furrow drip irrigation methods. Subsurface is slightly more water efficient but less cost efficient than exposed furrow irrigation [2]. Furrow drip irrigation techniques use 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 fix and adapt than surface or sub-surface drip irrigation; in these techniques, the irrigation lines lie on or below the soil surface. 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.

Insufficient irrigation adversely effects plant physiology and crop yield; if prolonged, this condition is known as *water stress* [40]. 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 concentration

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of sugars and development of flavinoids. Precision viticulture is an emerging area having increasing impact in the wine-growing sector [12, 15] and similar plant-level irrigation is desired for other high value crops such as almonds [38].

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) as the actuation method for a precision agriculture control 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 ability for the DATE to interface with emitters under positional and orientation uncertainty.

A. Related Work

The problem of spatially varying moisture measurement and simulation has been extensively studied [5, 10, 48] using models based on finite differences, nonlinear differential equations and partial differential equations. Temporal variability has been considered in [6, 7, 9]. Methods specifically aiming at modeling subsurface moisture with drip irrigation have been developed by [34] and experimentally validated. Building upon these models, several simulation packages are available for modeling surface, subsurface, and groundwater flow. Software packages like HYDRUS 2D/3D [3] or LandLab [13] have been used for modeling flow and designing drip irrigation systems [24, 43]. However, once these systems are in place there is no commercially viable method for actuating water output levels on a per plant basis.

Automated Irrigation Systems: Information regarding soil moisture level and evapotranspiration can be obtained through soil probes, near infrared (NIR) cameras, thermal sensors mounted on robots, remote or UAV mounted sensing, weather information, satellite imagery, or online services like the California Irrigation Management Information System (CIMIS) [1]. This information can be used to inform irrigation plans, but irrigation control is still accomplished commercially at the (coarse) block level [28].

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 pests such as the Northern Pocket Gopher *(Geomys bursarius)* [46] 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 [23]. The success of a precision irrigation system is contingent upon keeping distributed emitter and equipment costs low.

Mobile Robotic Platforms: Autonomous robotic systems are becoming an integral component in agricultural operations [18]. Distributed systems of UGVs operating autonomously as fleets have been explored as solutions to labor shortages in agricultural settings [52] and implemented as autonomous tractors for harvesting [32]. Following the commercialization of computer vision sensors, global positioning systems, LIDAR, and Inertial Measurement Units (IMUs), robotics research over the past two decades have led to many examples of unmanned robotic vehicles and service units in agriculture [26]. Several demonstrated uses of UGVs in agriculture include weed detection [19] and precision herbicide deployment [49]. UGVs with simple manipulators have been deployed for weed retrieval [16].

A precision irrigation system with distributed passive drip emitters could use a fleet of UGVs with robotic manipulators to adjust settings across large fields. The two-stage mechanical gripper system described in this paper is designed with the consideration that the DATE will be mounted on an autonomous agricultural vehicle such as the Jackal developed by *Clearpath Robotics*.

Grasp Planning under Uncertainty: The UGV with the DATE mounted on a robotic arm will be traveling through an outdoor agricultural environment with large variability in textures and scenic clutter. Recent work [22, 35, 45, 47] has 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 [21, 36, 42, 50] and object detection in cluttered environments [17]. Active exploration for robotic grasping has been explored in prior work [30, 33, 37, 41]. Methods for grasping unknown objects [14, 20] use active exploration to reconstruct the 3D geometry of the object before planning a grasp.

A sensorized approach to inspecting and grasping objects such as irrigation emitters could be taken as described in [11] where touch, range, sound, and vision sensors are fused to create an intelligent grasping system. However, we assume the DATE will be interfacing with a predefined emitter; we approach the problem by designing an emitter and two-fingered gripper that together overcome positional uncertainty when interfaced. Our design constraint for the emitter is that it remains adjustable in output and remains inexpensive (the emitter shown in Figure 2c costs $0.25 per piece).

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 such as door opening [25], since caging grasps allow increased flexibility compared to classical force closure grasps. The connection between caging and grasping has been investigated also by [44], who showed that increasingly tight cages can result in force closure grasps. The closing mechanism of our design

(a) Fixed-flow emitter
Base Diameter 0.75in

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

(c) Adjustable emitter
Cap 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. Both types of emitters are installed by inserting the barbed base into PVC water lines.

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

We propose a precision irrigation system with sense, actuation, and planning/control components. Sensing is accomplished with UGVs, UAVs, and mesh networks of soil moisture probes distributed through the field [8]. Feedback to the control system is accomplished through GSM/GPRS networks and ZigBee radios [29]. The control system schedules interactions with individual valves located at each plant to plan optimal routes for agents in the field based on weather, and field data. Actuation can be accomplished by teams of humans and robot workers moving though the field to collect data and adjust individual emitter settings based on the control algorithm.

Design Motivation: The DATE described in this work is designed to be used by human or robot workers in a field equipped with adjustable emitters similar to Figure 2c. The position of each emitter will be known to the control database; specific tuning parameters will be communicated to the DATE via a single once-daily upload from a base station via GSM/GPRS or ZigBee Radio. Each tuning operation will be associated with a GPS location and RFID for the associated emitter. The DATE will guide the worker to find the next emitter to be tuned in the field using onboard GPS (coarse) positioning and RFID emitter (fine) identification. Additionally, the DATE can be used by the worker to update control system field data such as emitter positioning and any sensor-network data collected locally via ZigBee radio as the worker moves through the field.

With thousands of emitters distributed in the field, the DATE (illustrated in Figure 1) is designed to minimize the difficulty and time in emitter locating, interfacing, and tuning. DATE has a mechanical gripper assembly to interface with emitters (shown in Figure 2) in the field which have been targeted for tuning. The gripper assembly is designed to passively locate and orient itself to the emitter through coarse and fine mechanical manipulator. The coarse mechanical manipulator (as shown in Figure 5) overcomes positional uncertainty in the worker's approach to the emitter and grips the base of the emitter. The fine manipulator then engages the cap of the emitter and provides the torque required to tune the emitter.

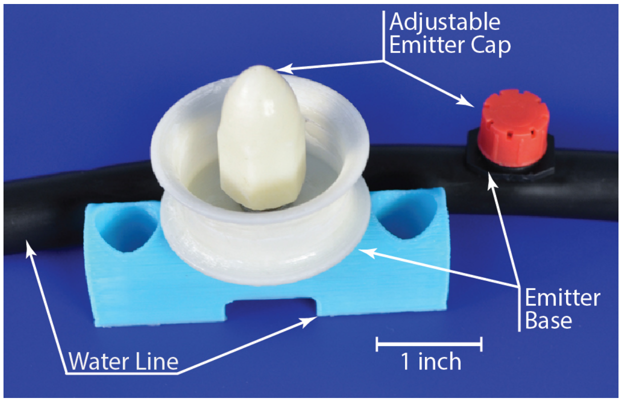

Fig. 3: The adjustable emitter (shown at left) redesigned to interface with the DATE. A commercially available design is shown at right mounted on 0.75 inch PVC irrigation line. The 45mm collar surrounding the redesigned (white) emitter is designed to aid in grasping.

II. SYSTEM DESIGN

Based on the motivations presented above, 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.

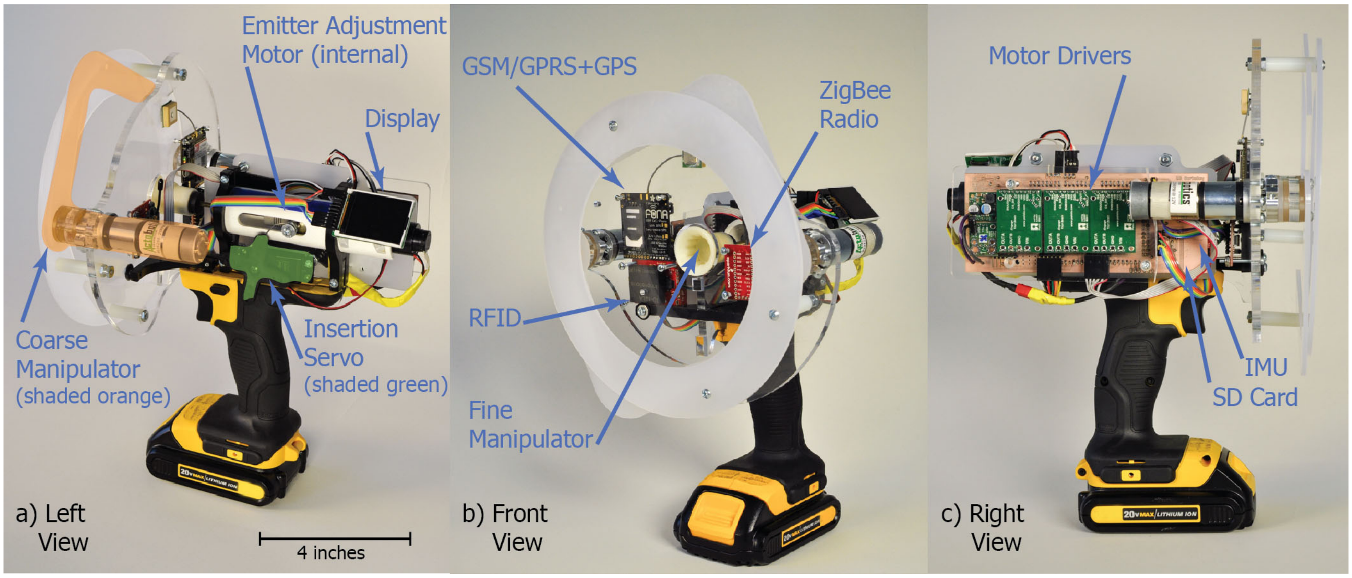

Fig. 4: The DATE in hand held form houses the sensors required for a worker or UGV in the field to locate and adjust emitters.

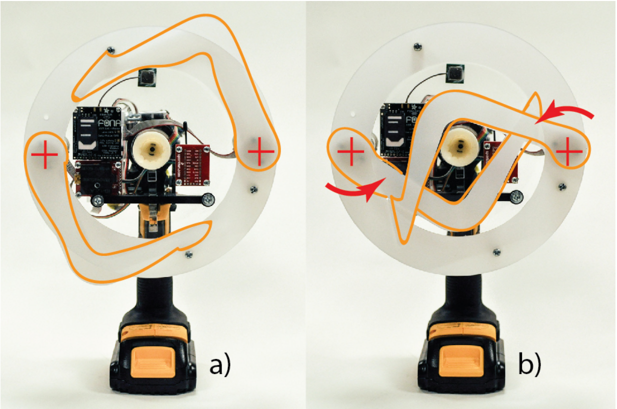

Fig. 5: The DATE is able to overcome positional misalignment by caging the emitter base between within its 1-DOF coarse gripper acting as a mechanical iris. The coarse manipulator fingers are outlined in orange; torque applied to center the DATE around the base of the emitter is illustrated in red. When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

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 that shown in Figure 3. 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.

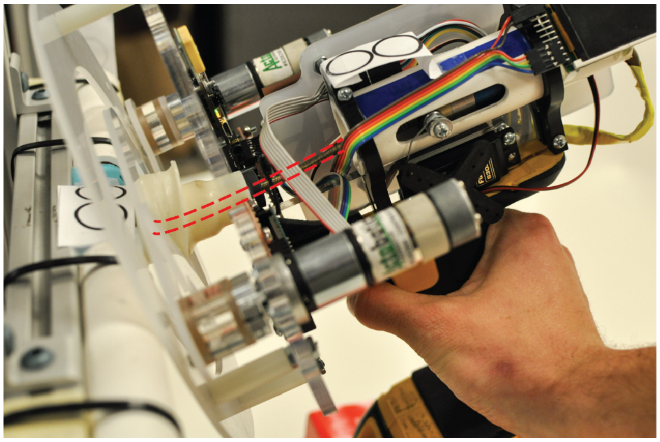

Fig. 6: After the base (collar) of the emitter has been caged, the fine mechanical manipulator inserts to engage the cap of the emitter. Torque to adjust the emitter cap is supplied through a flexible shaft (highlighted in red) that overcomes any remaining misalignment between the adjustable emitter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

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 to 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 inserts the fine mechanical manipulator 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 found using a Mediatek MT3337 22 Channel GPS accurate to 2.5m. Communication to existing Wireless Sensor Networks [29] is accomplished with an XBee Series 2, 2mW Wire Antenna, ZigBee Protocol Radio (XB24-Z7WIT-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. 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.

III. EXPERIMENTAL EVALUATION

An adjustable emitter was mounted to a section of irrigation line below a camera as seen in Figure 7. Template matching was used to record lateral and angular offset of the DATE with respect to the tip of the emitter. 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.

Specifically we are interested in validating:

1. Coarse mechanical gripping to locate and grip the emitter base,
2. Fine mechanical gripping to locate and transmit torque to the emitter cap with respect to the emitter base, and
3. The capture region of the emitter-DATE interaction at angular and lateral offsets.

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. Over 60 trials, the DATE had an overall success rate of %80 as seen in Figure 8. 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. 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 x-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 an overall success rate of %80, with a %90 success rate within the region -4.1cm 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 (-4.1cm to 4.3cm from origin).

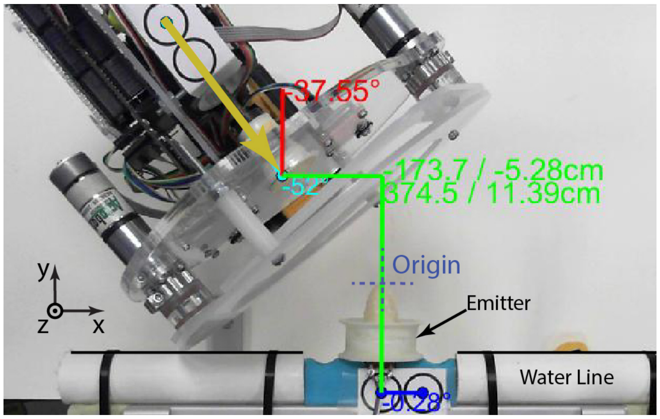

Fig. 7: A visual tracking system was used to record success and failure of grasping trials. Template matching was used to determine position of the DATE with respect to the origin (emitter tip). The yellow arrow represents the approach vector of the DATE to the emitter origin.

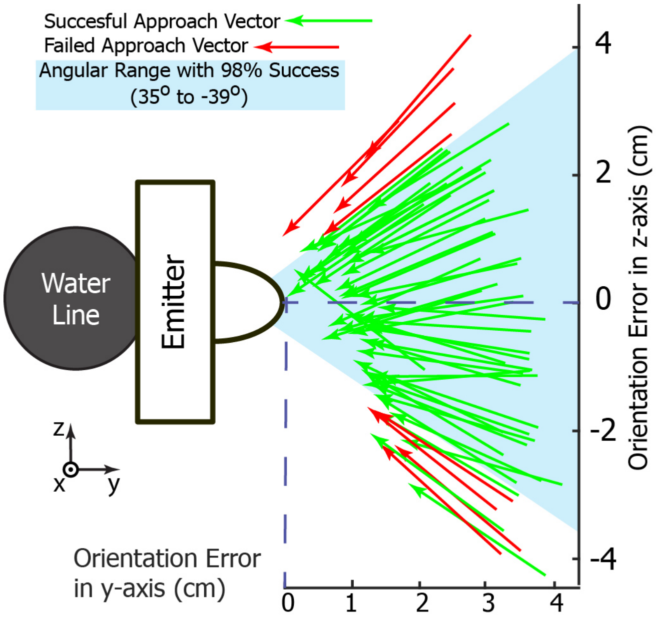

Fig. 8: The DATE's two-stage mechanical manipulators can overcome 74 degrees of angular uncertainty in interfacing with a 16mm diameter emitter cap in 98% of trials. Each arrow represents an approach vector from each grasping trial (see Figure 7) Green vectors represent successful gripper re-orientation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

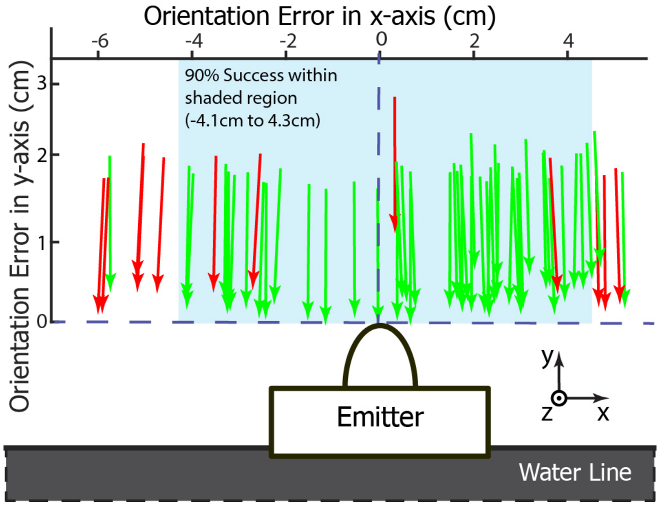

Fig. 9: The DATE can successfully grasp a 16mm diameter emitter cap despite an uncertainty range of 84mm in 90% of grasp attempts. Green vectors represent successful gripper re-orientation and positive emitter grasp. Red vectors represent grasp failures.

IV. 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. A UGV in the field using the DATE as a gripper to interface with irrigation emitters could relax its accuracy constraints to be within 4cm laterally and within 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.

The *Jackal* UGV by *Clearpath Robotics* is a developer platform for agricultural purposes which can be interfaced with a 6DOF *Kinova MICO* arm. After minimizing the overall size of the DATE, the authors will mount the gripper to the end of the UGV's arm. Field evaluations will be performed with farm managers and growers in the wine producing regions of California (Central Valley, Napa, Sonoma, and Mendocino Counties).

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