The Potential Applications of Robotic Technology in Wine Production

Prepared by:

RE2, Inc.
4925 Harrison Street
Pittsburgh, PA 15201
412-398-0949
info@resquared.com

March 31st, 2018

Contents

The Potential Applications of Robotic Technology in Wine Production

INTRODUCTION

For generations, viticulturists have primarily relied on their own skill for grape growing and harvesting. Traditionally, discerning healthy, plump grapes from those that may be rotten or unripe has been a task best suited to the human hand, eye and judgment. The cultivating, pruning and harvesting of grapes by hand is tedious, painstaking work—and therefore, costly.

Machines have been designed to specifically address vineyard needs. Mechanical harvesters, for example, have been used in the harvesting of grapes since the 1950s. While mechanical harvesting reduces costs and significantly increases output, mechanized harvesters do not have the ability to discriminate between ripe, healthy grapes and those that are unsatisfactory, rotted, unripe or simply clusters of leaves. Harvesters can also damage the vines and grapes, rendering them unusable or undesired.

The field of robotics presents a next-generation opportunity for farms and vineyards. Using intuitive, advanced technology such as precise manipulation, computer vision and machine learning, robotic machines have the potential to be applied to many aspects of grape farming, such as pruning, crop monitoring, yield estimation and harvesting. The adoption of robotic technology is dependent upon many variables, as is outlined in this report.

Representatives from RE2 Robotics and Texas A&M spent several weeks touring both traditional farms and niche vineyards in Texas, California, Oregon, Washington and New York to learn firsthand how robotics can assist in the cultivating and harvesting of wine and table grapes. From RE2, the team comprised of Keith Gunnett, Chief Technology Officer, and Reeg Allen, Vice President of Business Development.

RE2's goal was to learn how and why vineyards of different sizes and geographic location typically perform their vineyard operations. Particular attention was paid to the risks, problems and issues experienced by vineyard operators. Based on these results, RE2 would then identify vineyard operations that have the most potential to be automated with precision robotics to alleviate these risks and problems. In addition, the group surveyed vineyards to identify any potential barriers, whether real or perceived, to using robots in their operations. This included whether the vineyard has already implemented any form of mechanization and, if so, whether moving beyond mechanization into robotic autonomy would be economically and operationally feasible.

In each region we visited, we found both small, family-owned farms and larger-scale winemaking operations that could benefit from robotic technology, whether from complete automation or human-robot collaboration. Conversely, we identified several operational areas that we feel would not benefit, either operationally or economically, from the implementation of robotic technology.

What follows is a detailed explanation of our findings, including a breakdown of vineyard operations into their individual tasks; existing agricultural technologies, including those in research and development, that could be applied to vineyard operations; a summary of each region we visited; a look at what we consider to be the top markets for the use of robotics in vineyard production; and the technical and economic feasibility and challenges of the use of robotics in grape production.

VINEYARD OPERATIONS: INDIVIDUAL TASKS

To identify operational areas that could benefit from the use of robotic technologies, it's important to understand the individual tasks taking place over the course of a grape growing season. These include pre-pruning, pruning, shoot thinning, sucker removal tying/shoot positioning, canopy management, crop monitoring/yield estimating and finally, harvesting. Each of these tasks are explained in the sections below.

Pre-pruning

While finish pruning typically involves cutting a cane down to one or two buds, pre-pruning leaves approximately 12 inches of existing cane. While not all vineyards employ pre-pruning, those that do utilize the technique to prevent the spread of disease on the vine. Leaving extra inches of cane on the vine allows for a "buffer zone" that prevents disease from reaching the actual vine, since the diseased part of the cane can be removed before it reaches the rest of the vine. Moreover, pre-pruning adds several weeks to the growing season. According to Napa Valley Vinters, the non-profit trade association that promotes the Napa Valley winegrowing region, vineyards often employ pre-pruning during the dormant season to help retain their skilled workers, who have already been trained and who may leave to look for work elsewhere when production wanes. Pre-pruning typically takes place in the fall and winter. After bud break workers typically head back into the fields to prune down to the buds, closer to spring. See Figure 1 for photographs of vines before and after pre-pruning.

Figure 1: Pre-pruning operations typically remove all but 12-15 inches of canes during late fall or winter.

Pre-pruning is done both by hand and by mechanization. Pre-pruning mechanization, such as the use of tractor-driven pruning machines that ride over a row of grapevines, is estimated to be about 15 to 25 percent faster than pruning by hand. Pre-pruning also reduces the chance of injury, including repetitive stress injuries as well as injuries or cuts to the eye or face from canes that snap back from the wires.

Several companies offer mechanical pre-pruning attachments for tractors. Most of these pruners use a rotary comb to lift the vines and vertical trimmers to cut. This technology is in use in the Lake Erie region. An example of a mechanical pruning machine is shown in Figure 2:

Figure 2: A mechanical pruning system that uses rotary combs to lift the vines and vertical cutters to remove the excess vine.

Pruning / Finish Pruning

Throughout the winter, when the vines are fully dormant, farmers prune last year's growth. For farmers that pre-prune, this would be called finish pruning or in other words a second pass of trimming vines towards the end of winter. For farmers that do not pre-prune, their workers will complete the pruning operation in one pass. Pruning is an absolutely essential task for every vineyard, as it enables the vineyard manager to control the growth of the canes and remove diseased canes. The goal of pruning is to promote vine vigor and control crop size. Depending on whether cane pruning or spur pruning techniques are used, the vines are either left with four canes (cane pruning) or each cane is left with 2 buds respectively.

Figure 3: Cane pruning (left) leaves 4 canes which are trained across the cordons. Spur pruning (right) trims the canes to the bottom two buds.

As with pre-pruning, pruning can be done by hand or via mechanization. When done by hand, the average vineyard worker makes around 20,000 cuts a day using a pair of pruning shears. During our site visits, farmers reported that human pruning speed ranged from 9 to 40 vines per hour depending on vine conditions and skill of the worker. They also noted that hand pruning, and similarly pre-pruning, can lead to significant eye or facial injuries and repetitive stress injuries. "Super scissors," or electric, motorized pruning shears, can reduce potential injury, but are often heavy or uncomfortable to work with over a long period of time, and increase the danger of workers accidentally cutting themselves.

Adoption of more mechanization for the pruning process is likely as the labor force declines. However, some vineyards will continue the tradition of manual pruning in order to have absolute control over their crop. Large scale mechanical pruners are indiscriminate when removing vines, whereas manual pruning allows the vineyard manager to selectively prune based on parameters such as last year's growth, shoot density, cane vigor and others.

Shoot Thinning

As the growing season continues, shoot thinning is the selective removal of shoots on a cane to facilitate improved fruit size and fruit quality. It usually takes place throughout the spring when shoots are about five to six inches long. It helps to reduce vine stress during the growing season and reduces problems due to excessive canopy growth. Shoot thinning allows the grower to adjust and manage the number of shoots to achieve optimal distribution, density and leaf area needed to ripen the desired crop. Shoot density is limited and crop size is regulated by the act of shoot thinning. Shoot thinning down to the recommended three to five shoots per linear foot of trellis for vertical shoot positioning (VSP) is critical for both pest management and optimal fruit quality. To thin shoots, workers remove shoots at the node via hand, or by using a mechanical cordon brush, which is driven by a tractor.

Sucker Removal

Sucker removal is the act of removing some of the shoots that grow from old wood at the base of grape vines or underneath cordons. Because the majority of the suckers grow at the base of the grapevine, workers must constantly bend down and straighten back up to perform this task. This type of labor can have lasting physical effects on the workers' knees and backs. One alternative to manual labor includes the use of chemicals, however many farmers try to minimize the use of excess chemicals. A mechanized alternative is the battery-operated EPAV2 tool developed by Infaco. This lightweight tool works like a string weed trimmer and removes the sucker while improving worker comfort and safety.

Tying/Shoot Positioning

Shoot positioning is an important task in vineyards. The goal of shoot positioning is to create a uniform distribution of leaf canopy that minimizes the shading of the fruit. An open canopy is essential to the productivity of the vine as well as fruit quality and disease minimization. Not only is shoot positioning important for the current growing season, it also has an impact on productivity in the following year. Sunlight encourages the development of more fruitful buds for next year's crop.

Vertical Shoot Positioning (VSP) is a vine training system in which growth is trained upward from low cordons. A VSP trellis system can consist of four to six levels of wire. The cordon or fruiting wire is typically 3 feet off the ground. Above the cordon wire are movable catch wires to train the growth of the shoots in an upward direction. Shoots can then be trimmed at the top. The top wire is usually 60-70 inches high. However, the height can be adjusted if necessary.

Catch wires are an important component of the VSP. They are the portion of a vertical shoot positioning training system that is used for shoot growth placement. Catch wires can be fixed or moveable. Some growers use fixed catch wires. This requires workers to manually tuck shoots in behind the catch wires. The disadvantages of fixed catch wires include the increase probability of breaking off shoot tips and the time it takes to perform this task. Positioning shoots manually is very labor intensive. Moveable catch wires can be moved up the post as necessary or can remain stationary if movement isn't required. This is a physically demanding task but less labor intensive than manually positioning every shoot along a fixed catch wire. There is less potential to damage vines in the process. It is also considered more efficient to move wires up/down to sweep foliage into an upright position, compared to tucking foliage between fixed catch wires.

Leaf Thinning

Leaf thinning, or canopy management, is the process of removing leaves from the vine in the area around the fruit clusters, typically immediately above and below the fruit. If done properly, leaf removal can improve air circulation, increase penetration of fungicide and insecticide sprays, expose fruit to more sunlight, and improve overall fruit quality – including flavor and color. Leaf thinning may be required multiple times during the season. It is important to not remove too many leaves; otherwise, vine growth, ripening, and hardiness could be negatively affected by too much sun exposure. Although typically a hand labor task, there are a number of mechanical leaf removers on the market. Mechanized leaf removal operators must be trained and skilled in order to perform leaf-thinning tasks without damaging vines, flowers, or fruit. One such electro-mechanical leaf removal system on the market is from Pellenc, a French agricultural mechanization company. This system requires installation on a tractor and an operator. Current mechanical canopy management systems are not selective when trimming leaves, and therefore this mechanization may not be considered acceptable when the quality of the grape is higher priority than the economics of its production.

Crop Monitoring and Yield Estimating

Crop monitoring and yield estimation provides growers with information on crop growth and prospective yields over the course of a growing season. Crop monitoring allows growers to gauge the health of their crops and to make adjustments as necessary. Because it impacts a vineyard’s bottom line based on potential yield, an effective crop monitoring system is crucial, no matter what the size of the vineyard.

Yield estimation is also important for growers to approximate labor demands during harvest, and, if selling grapes to a production facility, to establish/refine fruit sales contracts. Crop monitoring, including sugar estimation, is important for wine producers to determine and prepare for blending of fruits to achieve their desired products.

Harvesting

Harvesting takes place at the end of the growing season, and the timing of the harvest is the most important decision a grape grower makes. Harvest time is obviously determined by the ripeness of the grapes, and the flavors that the vintner is striving to achieve. In California wine country, harvesting can take place as early as July, but the majority of grapes across all parts of the country are harvested between August and October. Overall, the process takes about two months per year, depending upon the season's weather, labor availability and the crop size. Since grapes ripen at different rates, winemakers determine when to harvest their grapes by testing the sugar content of the grapes. While some winemakers determine ripeness using the old-fashioned method– by simply tasting the grapes—others determine ripeness using a hydrometer or refractomer, which are a tools that measure the level of sucrose, or sugar, at a specific temperature in a grape cluster. This measurement is known as degree Brix.

For table grape growers, the harvest includes not only the removal of grape clusters from the vine but also the in-field packing of grapes in market-ready containers. These containers are placed in larger bins that are then transported to the storage/ staging area. Since workers are paid by the container on many farms, the time spent moving the containers from the picking area to the bins at the end of the rows where tractors pick them up is non-value added effort.

Mechanical harvesters, which use an over-the-row machine that shakes the fruit off of the vines, have been in use since the 1950s-1960s. Despite the benefits that mechanical harvesting offers, many wine makers often still prefer to harvest grapes by hand, which is both time consuming and dependent upon the availability of laborers. There is also a perceived quality applied to hand-picked grapes, which convey an "artisanal" quality to the finished wine product.

VINEYARD VISITATION SUMMARIES

Between July 2014 to March 2016, RE2 and Texas A&M personnel made site visits to grape growing regions across the US.to survey the similarities and differences in vineyard operations. The states visited included Texas, California, Oregon, Washington State and New York. Visits were at several different time periods of the grape growing season so that the team could see a wide variety of the types of vineyard operations in practice. Summaries of each site visit are included below.

Region: Northwest Texas

In July of 2014, the first region the team visited was the Lubbock, TX area in Northwest Texas. Northwest Texas is a large, rural agricultural area. In this very dry desert like area, a large variety of crops, such as cotton, almonds, vegetables and grapes, are grown on massive farms that often encompass several thousand acres. Grapes are a relatively new crop to this region and are rarely the primary crop of any of the farms. In this area of large, professional farms, the growers have found that dedicating several hundred acres to high value wine grapes out of their thousand plus acres of operations is great way to diversify and reduce their business risk. It is important to note that grapes are usually not their primary crop. These farmers are also not in close proximity of wineries, nor are they generally in the business of producing wine.

Figure 4: Pictures of a Texas vineyard visited on the July 2014 trip. These pictures show the typical dry, sandy conditions in Northwest Texas as well as the thick canopies in this region that can make the automation of several vineyard tasks such robotic harvesting difficult.

Rather, they sell and ship their grapes and grape juice most often to small vineyards or wineries in the Texas Hill Region, which is known for its tourism. Additionally the Texas vineyards have found some business shipping to other wineries across the US

Competition for labor can be a major issue in this area. Northwest Texas is a very large rural area with a small population. Also since this a very large and diverse agricultural region growing many crops, seasonal workers migrate to the crop or area that pays the best, often leaving a shortage of workers for other crops. The vineyard portion of farms in this region are relatively large; the average-sized vineyard in this area is 200 acres, with the largest vineyard visited consisting of 520 acres. Northwest Texas farmers rely heavily on mechanization and automation for their primary crops such as cotton. Therefore they are very open to using mechanization and automation for their secondary grape crop. Grape harvesting is primarily automated, as is the majority of pre-pruning.

While the majority of these farms are already heavily automated, we did recognize several potential applications for robotics. For instance, robotic technology could be beneficial in the finish pruning of vines, as well as in yield and crop estimation. Secondary to those applications, a robot could be used to assist with crop thinning, sucker removal and shoot thinning.

Region: Central Valley, California (Table Grapes)

In the middle of the harvest season of September 2014, the team visited large, table grape growers in the Central Valley of California south of Fresno, CA. These grape growers are large, structured corporate enterprises. 85% of the table grapes produced in the US, which several reports have stated is close to a $2 Billion market, are from the hot and dry Southern San Joaquin Valley. Table grapes are very sensitive to rain which can blemish the skin of the grape. The very dry conditions of the San Joaquin Valley is therefore extremely well suited for table grape farming.

The presentation or visual appearance of a table grape is the key factor when selling this grape variety and therefore is a major driver in the agricultural practices of this market. Due to the high importance of visual quality required for table grapes, vineyard operations in this grape market are very labor intensive since they are nearly all done by hand. During the trip, the growers interviewed reported the following as their top labor cost for vineyard operations:

1. Harvesting
2. Thinning:
    a. Shoot Thinning. An expensive, labor intensive activity done by hand
    b. Cluster Thinning. A labor-intensive activity done in the narrow window of May to June at an average rate of 25 vines / person / hour by hand.
    c. Bloom Thinning. Currently done chemically which prevents workers from entering these fields for 3 days after application.
3. Pruning

At over $4,000 per acre, hand harvesting, which includes sizing, cleaning, and packaging, is the most labor-intensive vineyard operation for table grapes. Size and presentation are key perimeters for getting the best sale price for table grapes. While grapes within a particular field / block grow and ripen at similar rates there is enough variation that grape rows need to be picked with multiple passes, as high as 7 pass and as low as 2 on a single row, in order to harvest the best quality. Grape clusters that are not mature or ripe enough are left on the vine to continue to grow and ripen which causes the need for additional picking passes. During a picking pass, grape clusters, chosen by size and ripeness, are trimmed by the picker and placed in totes. After filling several totes, the picker uses a special wheelbarrow, modified to carry the totes, to transport the grapes to a packing station at the end of the row. A very common practice for table grapes is to pick and pack them into bags or clamshell packages right in the field and then move them into cold storage quickly to preserve quality. Given that the temperature of the grape at time of picking affects quality, the ability to improve the efficiency of picking during the cooler morning hours or creating the ability to pick at night has a lot of potential to improve table grape operations.

We identified four major areas for table grapes that would benefit from the use of robotics. First, during harvesting, robotics could assist with selective cluster picking, in-row transport, and cluster cleaning. Secondly, these vineyards could benefit from automated crop monitoring (such as monitoring for pests) as well as crop and yield estimations. Thirdly, robotic systems could aid in the trimming of shoots and leaf clusters. Finally, as with the Texas farmers, robotics could help in the pruning of vines.

Region: Central Valley, California (Raisins)

We also visited raisin producers in the Central Valley of California. Unlike table grape producers, raisins are typically grown on small (e.g. such as 10 - 20 acres) farms whose owners work together in a cooperative agreement.

Since raisins are a lower-dollar crop, they do not require the same attention to detail as table grapes or fine wines. As such, there is no need for human-type perception to distinguish healthy grapes from rotted ones. Mechanized harvesting is already in place on most farms. After the grapes are removed from the vines, they are laid out on paper mats and left to dry for several weeks.

The majority of the farm is already mechanized, and since the harvesting of grapes for raisins does not require a keen eye or gentle selection, there is not much need for robotic technology. A robotic system could be adapted to help cut and pull dried canes or for shoot positioning; however, robotic precision is not necessary for these types of tasks.

Region: Oregon

In March 2015 at the end of the pruning season and beginning of the preparation for the growing season, the team went to the northwest to the wine vineyard operations of Oregon and Washington. During this trip, the team observed pruning and tying operations. In Oregon, we found a vineyard region that is very similar across the board and highly driven by marketing and tourism. White wine dominates the region and the vineyards in Oregon tend to be small (10 acre plots are typical) as compared to other wine grape regions of the US. In Oregon, it is very common for the vineyard and the winery to be the same location. The focus of the region is on premium and higher end, ($30 +) white wines.

Because the Oregon market focuses on higher-dollar value, niche operations, the perception of quality is extremely important in this market. Perception of quality and the small size of the vineyards are the key drivers in the decisions of how vineyard operations are conducted in Oregon. Marketing terms such as "Hand Crafted" and "Organic" can be weighed more heavily in this region versus pure economics when it comes to making decisions on how to operate a vineyard. Because of this, there is a high demand for skilled, hand labor, as a majority of harvesting and pruning is done by hand to assure the best selection. Some of their tasks, such as cane pulling, are automated (but not robotic) with limited success. However, most of the work is manual and therefore labor-intensive and expensive; these tasks include shoot positioning, sucker removal, and pest control. One of the most labor-intensive activities reported by farmers in Oregon is in field hauling of fruit. In a similar fashion as table grapes, fruit is picked into buckets and then carried by the picker to the end of the row. The farmers felt that automation of this task would help efficiency.

The Oregon vineyards we visited could benefit in numerous ways from the use of robotic technology. For instance, robots could assist with in-row transport of the grapes, as well as crop and yield monitoring (i.e., inventory control). Moreover, robotics could assist with pruning and cluster trimming. Robots could also help with secondary leaf removal after the machines have passed through.

Region: Washington

On the second half of our northwestern trip, the team visited the vineyard region of the State of Washington. When it comes to wine production, Washington ranks second in the country behind California. Nearly all of wine grape production takes place in the very rural, sparsely populated agricultural area in the eastern half of the state, which, thanks to the topography and "rain shadow" of the Cascade Mountain range, is nearly desert-like. Also due to the rural nature of the area, seasonal hand labor can be hard to find and tourism is not a major consideration unlike the California regions of Napa or Sonoma.

Given the characteristics of the region, Washington grape growers tend to be massive, corporate productions. One of the vineyards the team visited is approximately 3,700 acres and produces high volumes of wine grapes for low-to mid-dollar wines. Most of the grapes grown in this region are hauled to corporate wineries such as Chateau Ste Michelle Wine Estates that mass-produce large volumes of wines to be sold around the world.

Driven by the market condition of the region, the vineyards in this area are highly mechanized. Most of the harvesting, pre-pruning / pruning and sorting is already mechanized and automated, leaving little need for tasks to be robotized. However, there is a little bit of opportunity for robotics in this region for finish pruning and crop yield and monitoring. Both of these tasks still require some hand labor, but the need for this technology is nowhere as great as it is for other regions.

Region: New York

In July 2015, during the middle of the growing season, the team went to the Finger Lakes region of New York to visit the wine grape vineyards. We found that this vineyard region is similar to Oregon. Cane pruned white wine dominates the region and the vineyards tend to be small compared to other wine grape regions of the US. The area is tourism driven, since it is a summer vacation destination, which leads to a high percentage of co-location of the vineyard and the winery. One large difference is that the New York wines are not as heavily marketed and the area, on average, does not command the same dollar value per bottle as Oregon.

Given the economics and characteristics of the region, New York vineyards are in the middle when it comes to hand labor versus highly mechanized operations. The area receives a great deal of rain fall compared to other regions so managing growth, rot, and dieses is a large challenge of this region. (See Figure 5 for an example of excess growth in a vineyard we visited.) To manage some these issues, precision mechanical spraying is deployed in the fields up to 14 times per year. Unlike Oregon, mechanized harvesting is used heavily in this region. That said, cane pruning and pulling, which causes repetitive stress injuries, as well as shoot thinning is predominately done by hand. Movement of catch wires is also done by hand and given the height of the trellis system utilized in NY, can be a challenge for many of the seasonal workers.

Figure 5: Pictures of a typical New York vineyard with a great deal of vine and non-vine growth in the vineyard due to the rain fall levels in the area.

While there is a moderate amount of mechanization in the New York region, we did recognize several potential applications for robotics. As with all the regions visited, a robot that can effectively do crop monitoring and estimating would greatly benefit the region. This is especially true if it can nondestructively sample the ripeness of grapes

Similar to other regions, the New York vineyard managers would like to maintain a core group of skilled workers and minimize the need for a seasonal spike labor force. In New York, the operations that still require a spike in the seasonal work force are pruning, tying, shoot thinning, catch wire movement and sucker removal. If a robot could be developed with an accurate vision and decision-making system such that it could selectively prune, pull brush, tie vines, and remove suckers, it would be of interest to this vineyard region. The cane pruned method and heavy growth of this region makes the design of such a system very challenging. In regards to catch wire movement, a good mechanical, not necessarily robotic, wire-raising machine would also be of interest.

Region: Napa Valley, California

In March of 2016, the team meet in Napa Valley, CA with several vineyard operations managers from 3 of the top 10 corporate wineries in the US as well as faculty members from UC Davis agricultural center. During our discussions, we determined that Napa is its own micro market and does not accurately represent the rest of California. The area focuses on growing high dollar red wine grapes with Cabernet Sauvignon being the leading varietal grown in the area. Napa is marketed more as a vacation destination than as a typical agricultural area, therefore the economics of the area are driven more from a tourism model than an agricultural model.

Napa Valley is driven more by presentation and prestige than by lean, cost cutting agricultural practices, which aligns with the nostalgia of traditional growing methods such as hand harvesting. The adoption of mechanization appeared to be limited in this area because it does not fit well with the "hand crafted" vineyard narrative of the region.

Napa Valley only represents 45,000 of the 615,000 total acres of wine grapes in CA, as reported by the Wine Institute and 2016 USDA NASS California Grape Acreage Report, and the economics of the area are mainly influenced by tourism. Therefore, it is the recommendation of this survey that the area be treated as an outlier when considering the utility and potential of robotics in CA vineyard production.

While Napa was the initial focus of our discussions, after it was determined that its economics did not represent that majority of California vineyards the discussion turned to understanding the rest of California. During this discussion we discovered that California vineyard operations vary greatly across the state from totally hand produced to highly mechanized operations. While the region the vineyard was located in had some influence on the operation style, it was less impactful than the variety or desired price point of wine being grow at the particular vineyard. The target price of the wine was the greatest factor towards deciding the vineyard practice being used. Bottles of wine that sell for less than $20 / bottle were from heavily mechanized operations and high priced wines that sell for $50+ were mainly hand crafted operations. The operations for the wines in between those two price point varied on a scale from heavily mechanized to highly hand crafted depending the company's desired practices and availability of labor.

The style of vineyard operations in California vary greatly across the state depending on the market the vineyard is producing grapes for. Therefore, the potential for robotics is generally not consistent across the state at this time. That said, a robot crop monitoring and yield estimation make sense for most, if not, all vineyards. Robotic pruning and thinning could become even more important as the labor shortage continues to grow. For vineyards that use manual labor for harvesting, in-row transport of grapes could be made more efficient through robotic vehicles.

Trip Summary by Region

Region	*Type*	*Market*	*Potential Tasks*
TX	Wine	*Professional, diversified farmers *Large Farms *Heavily automated *Sell and ship grapes to winemakers	*Pruning *Yield/crop estimation *Shoot thinning *Sucker removal
CA	Table Grapes	*Large, Corporate enterprises *Quality is essential *Labor intensive *Expensive Crop	*Harvesting (selective cluster picking, in-row transport, cluster cleaning) *Yield/crop estimation *Shoot thinning *Pruning
CA	Wine	*Diversified family farms/sole proprietors *Large, mass producers *Mechanized harvesting prevalent with mass produced wines *Tourism drives small regions to use hand labor for quality perception	*Pruning/ Cluster thinning *Crop monitoring and yield estimation *In-row transport of fruit
OR	Wine	*Professional, small-to-medium operations *Grow, produce and sell their own wines *Labor-intensive *High quality *Niche Market	*Crop monitoring and yield estimation
WA	Wine	*Very large, corporate production *High-volume, low to mid dollar wines *Ship to corporate wineries *Heavily mechanized/automated	*Crop monitoring and yield estimation
NY	Wine	*Professional, small-to-medium operations *Grow, produce and sell their own wines *Labor-intensive *Niche Market	*Crop monitoring and yield estimation * Pruning/Cluster thinning *Shoot thinning *Sucker removal

During our trips across the US we experienced a great variety of vineyard operations that ranged from predominately hand labor to almost totally mechanized. We found that there are a few key takeaways from these trips that help explain why vineyard operations use the system that they do and they are:

- All farmers would like to avoid seasonal spike labor if they could. As a whole, across the US the availability and skill of this work forces is decreasing.
- Ideally farms would like to have a steady skilled workforce that is capable of managing the farm year round
- The type of vineyard operations used are greatly driven by the dollar value of the wines the grapes are being used to produce. Generally lower dollar wines drive more mechanization, higher dollar less mechanization.
- Agricultural practices are also driven by whether the area is more of a tourist destination vs a rural, sparsely populated agricultural area (example Napa & Oregon vs Washington & Texas).
- Vintners drive the growing methods by perceptions of "quality", which are not always science based or the most economical ways to produce the grapes.

RECOMMENDATIONS FOR ROBOTIC APPLICATIONS IN THE VINEYARD

The sections below detail our recommendations based on site visits and research. These recommendations factor in the following criteria: Existing mechanized tools or machines on the market; the economic aspect of using robotic technology; and the state of the technology to accomplish the task. Following this section is a summary of the Existing and Emerging Technologies.

Pre-Pruning

Pre-pruning is task that is already highly mechanized with adequate results. The mechanical methods are quick, cost effective, and do not require a seasonal workforce to be accomplished. Given these characteristics this study does not recommend that this task be developed into a precision robotic task.

Finish Pruning

Finish Pruning is a labor-intensive task that this study recommends should be automated with precision robotics. From a market perspective, there are several reasons why using robotics to accomplish finish pruning is considered advantageous. Feedback from all regions in the site visits stressed that the large spike in seasonal labor needed to accomplish manual pruning was becoming increasingly difficult to find in many rural agricultural communities. In addition, the pruning task requires skill and decision-making from the worker. Skilled workers in a seasonal workforce can be hard to get, particularly since finish pruning is a time sensitive task that all vineyards are trying to accomplish in the same time window in any given region.

Unlike other vineyard tasks where mechanization has been widely implemented, current mechanical pruners are not accurate enough to maintain high-quality finish pruning. Many farmers are reporting that vineyard operations that have gone to just mechanical pruning operations such as the Oxbo and Pellenc mechanical pruners still need hand pruning to maintain the quality of the vines. The accuracy of maintaining horizontal spacing can be lost over time when only mechanical pruning techniques are used.

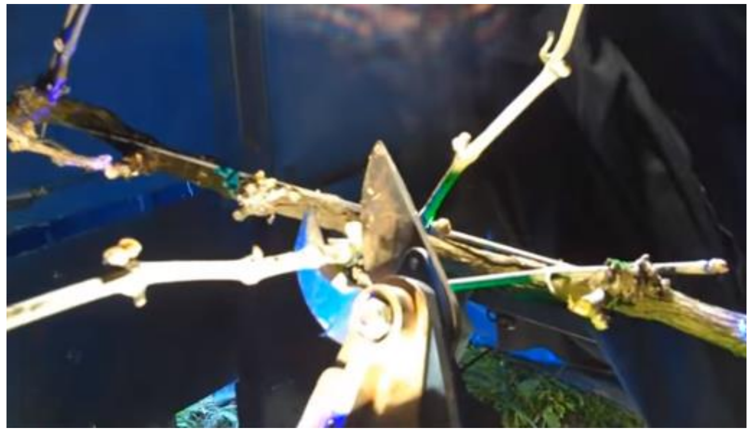

Figure 6: End effector with a pruning tool

From a financial standpoint, the cost of $300-500 per acre is a relatively expensive vineyard task. This level of cost has the potential of justifying the capital cost of purchasing and maintaining a complex machine. Considering that a robotic vehicle can work 24/7 if it has control over the lighting conditions, investing in technologies that enable rapid decision making and pruning action will determine the economic benefit of using robots for finish pruning.

In addition to the market rationale, the technical characteristics of pruning also make it a good candidate for automation via precision robotics. Since pruning is done in a dormant season, there is little to no foliage to inhibit vine perception by computer vision. Using mechanized pre-pruners to remove the bulk of the previous year's growth allows good access to the vines by a robot with reasonable effort. Having minimal obstacles also allows for a simpler and achievable decision matrix versus other vineyard tasks (such as shoot tying or positioning). The development of a robotic pruner is also aided by the relatively simple end effector that is needed for cutting soft canes.

In summary, the development of robotic systems for finish pruning is recommended as it balances the issue of needing a skilled labor force for a short period of time with technology advances that are reasonably available in the near future.

Sucker Removal

Sucker removal, the removal of extra shoots on vine trunks and cordons that take away nutrients from fruit growth, was reported to be a low cost task at less than $100 per acre. Current manual and chemical methods are adequate and, in general, this is not as time sensitive or does not require a major additional spike in the seasonal labor force like other vineyard tasks. That being said, it would rank as one of the simpler tasks that could be performed by robotics since:

- The vision task is conceptually simpler than other vision related tasks such as pruning and harvesting since this occurs on pruned vines early in the growth season. This allows for easier vision processing of new shoot growth when foliage is minimal.
- The manipulation requires minimal dexterity, force, and precision.
- A simple string trimmer or brush end effector is all that is needed since a minimal amount of force is required to separate the unwanted growth from the vine.

Figure 7: An example of sucker growth on a vine trunk that was not removed early in the growth season

Given the minimal economic and labor impact of sucker removal, this study only recommends the development of this robotic capability as a secondary task for an existing mobile, robotic platform that has navigation, manipulation and vision capabilities for performing its primary tasks.

Shoot Positioning

Shoot positioning is not a recommended task to be aided by precision robotics. Shoot positioning is of low economic concern and does not typically demand a large spike in seasonal labor. The robotic system required to perform the task of shoot positioning would be quite complex. Fine and delicate manipulation is required for this intricate task, as it is akin to basket weaving. The robotic system must be capable of making complex decisions to determine how the shoots should be positioned in accordance with the trellis system to increase air flow and sunlight to improve fruit quality and reduce disease pressure.

As part of the shoot positioning process for the vertical shoot positioning (VSP) training system, catch wires are raised as the shoots grow to retain the new growth. The operation of raising the catch wires requires strength and coordination. We do not see this task as wholly suited for robotics, but there is potential for an automated assistive mechanism. Basic mechanical assistance is recommended as a precursor to robotic automation. Perceiving the grouped catch wires is a complex vision, decision, and manipulation problem. Initial catch wire location should be considered for automation.

Figure 8: Shoot positioning is a task that is not recommended for robotic application in the near term

Shoot Tying

Shoot Tying is the process of tying the renewal vines and canes to the trellis wires. The process differs depending on the training system. It involves positioning, wrapping, and tucking of canes around the trellis wires and securing them with a mechanical tie. It is a labor intensive process, but is not performed in peak season. Workers are quick at this task using either hands or mechanized tools for the actual tying operation. There are quite a few mechanical tools commercially available that allow for efficient manual shoot tying. We've found the economics of robotic automation of this task to be questionable. The robotic system required for this task requires a high degree of dexterity, coordination, and decision making to correctly manipulate and tie the vine growth to achieve the desired outcome. It does not appear that shoot tying is an economically feasible application for robotics in the near term.

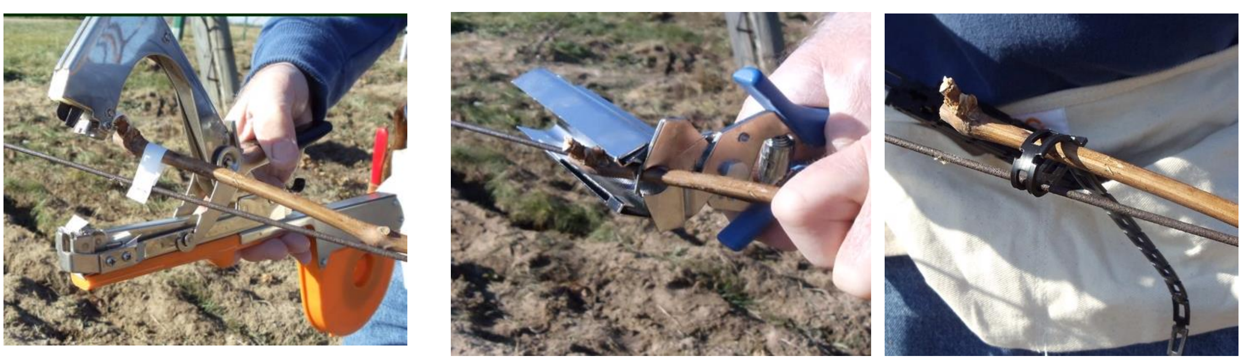

Figure 9: Examples of manual shoot tying tools available. The left-most image uses paper tape, the center image uses metal staples and the right-most image shows a plastic tie.

Leaf Thinning

The current state of mechanization for leaf thinning was determined to be adequate. This task only costs approximately $35 per acre using currently available machines. Farmers reported that the machines work close enough to human quality for their operations. During site visits, farmers felt that that existing leaf thinning machines are adequate, but there is room for improvement on controlling the head of the cutter. Based on this feedback and the availability of cost-efficient methods, the use of precision robotics does not seem to be justified for this task.

Figure 10: Current leaf thinning mechanisms are effective

Crop Monitoring and Yield Estimation

Crop monitoring and yield estimating are cost prohibitive and labor intensive tasks that this study recommends should be automated with precision robotics. Typically, vineyard managers will send survey teams into the fields several times a year to report on crop development. This feeds into yield estimation which allows planning for workforce labor size, harvest dates, and quantity of grape output. Some crop monitoring is currently being done with UAVs, but we believe that augmenting or replacing with ground vehicles will provide significant benefit to the grape industry.

One major advantage of robotic ground vehicles is that they provide better viewing angles of the ripening fruit than UAVs. This allows precision mapping of the vineyard to provide the vineyard manager with accurate data for: cluster counting to allow prediction of final crop yield; quality assessment of the fruit; early detection of disease; and signs of vine stress, to name a few. Existing ground vehicles can be programmed to traverse through the vineyard taking images of the vines throughout the growing season. Comparing the progress of the fruit development over not only that growing season but also year to year will aid the farmer in efficiently producing top-quality, high-yielding fruit. By collecting vast amounts of data covering a multitude of measurement types, researchers can help farmers correlate quantities and qualities which are difficult to measure to those more easily measured. The fusion of comprehensive data sets could provide farmers with new information to make decisions throughout the growing season. In order to produce useful data for the customer, complex data processing can condense results to easy-to-interpret heat maps and summary charts, allowing farmers to interpret current and historic data more easily.

Significant research is ongoing in this area and some robotic monitoring platforms have been demonstrated (e.g. VineRobot and VineScout). In the United States, the Efficient Vineyard project has research focused on crop estimation and crop balancing. Automating the outcome of the vision capture and data processing research onto robotic vehicles that can accomplish these tasks 24/7 (as needed) would be an economic advantage to grape growers of all sizes and regions.

Weeding

Weeding and soil aeration are ideal tasks for robotic vehicles. With GPS knowledge of row locations, and a vision system to keep proximity to the vines, a weeding attachment can be easily integrated onto a robotic vehicle. The weeding tool could be set to the proper depth for the particular varietal and sent out into the vineyard day or night. This task could also be performed in conjunction with crop monitoring, depending on the lighting conditions needed for the latter task.

Figure 11: A robotic vehicle performing autonomous weeding

Harvesting (Wine)

The task of harvesting wine grapes presents similar problems for vineyard managers as those found with finish pruning – primarily the need for a sudden spike in the labor force for a relatively short period of time. Unlike finish pruning, skilled workers are not particularly required to accomplish the task satisfactorily. Workers who manually harvest wine grapes can discern between healthy and diseased/ rotten bunches, which mechanical systems cannot. Workers will also tend to inject less MOG (Material Other than Grapes) into the picked fruit than mechanical systems do, which indiscriminately beats the vines to loosen the bunches of grapes.

The comparative use of manual labor, mechanical harvesters, or precision robotic systems is heavily driven by the price point of the produced wine. Lower cost wines are driven by the economics of producing an acceptable wine at a low enough cost, and quality is not the primary consideration. For such producers, robotic precision, cognitive processing and selective harvesting are not important parameters compared to cost and efficiency. This may change over time if the availability of low-cost labor continues to decline.

Figure 12: Manual harvesting is still the preferred method for mid-to- high priced wines

The use of precision robotic harvesting for moderate and high priced wines (>$20), as opposed to hand harvesting, **requires a marketing campaign** to combat the romantic notion that grapes which were not harvesting by direct human contact and labor produce an inferior product, and thus cannot demand the desired cost. Site visits to Napa and Oregon highlighted the entrenched belief that hand harvesting of grapes for mid to high priced wines was a necessity. In reality, the quality of robotically picked fruit could one day be equal to or superior to manual picking since the vision processing system can be programmed with images of "ideal" bunches and inferior fruit is bypassed.

While the perception of manually picked grapes is an emotional one, the reality of the current technology to enable robotically picked grapes is less rosy. At harvest time, the vines are heavily laden with red or green grape bunches, green leaves, and brown shoots. Computer vision for locating the grapes among the leaves as well as complex manipulation planning to avoid obstacles in order to achieve the desired grasp is difficult. The extensive and time-consuming process required for locating and detecting the grape clusters, planning the manipulator and end effector motions, and delicately collecting the fruit slows the robot and raises the cost. The end effector design is more challenging in that it needs to gently grasp, cut, and place the grape clusters from the vine to a container in order to preserve fruit quality.

In summary, being able to match the cognitive processing and speed of human hand harvesting with robotics is not currently achievable in the near term. Continued research and development in computer vision and machine learning is necessary to match human speeds. Long term funding for these topics is encouraged as severe labor shortages and/or increases in labor costs could justify precision robotic harvesting.

Harvesting (Table Grapes)

While robotic harvesting of wine grapes is not foreseen in the near future, the application to table grapes is quite different. Table grapes can ripen at different times on the same vine due to differences in sunlight on the fruit and cluster position on the shoot. While spike labor is still required at harvest time, a longer duration harvest allows for multiple passes and may allow for a shared workforce among regional farms. Another distinction between table grapes and wine grapes is that canopy management of table grapes is highly controlled and results in less foliage and more uniform location of grape clusters. Therefore, the fruit is in a better position on the vine for detection by computer vision, as it is not obscured by excessive foliage. Having improved cluster visibility makes the vision algorithms for determining green grapes from the green leaves a more manageable problem.

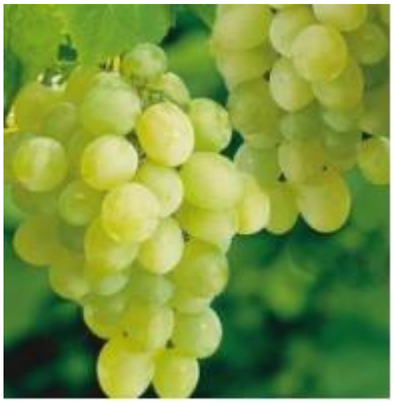

Figure 13: Thompson Seedless grapes are judged by consumers for color and size

Since consumers of table grapes mainly judge the fruit on visual qualities, the harvesting of these grapes must be done with care to inspect and trim rotted or irregular grapes. These factors eliminate mechanical harvesters from consideration. It is ideal to harvest table grapes when temperatures are lower to extend the storage life for acceptable quality of the product. For human operations this requirement limits work hours from sunrise to mid-morning. In order to harvest when temperature are lowest, autonomous robotic operations throughout the night would be possible with artificial lighting. Robotics harvesters can work longer, steadier and for multiple shifts – which is necessary for optimal, multi-pass harvesting.

Not only is the technology more suited for table grape harvesting than wine grapes, but the economic benefits are also heavily favored as well. Table grape harvesting costs are roughly 4-5 times those of wine grapes. That cost differential is significant and could certainly justify the cost of a robotic harvester, assuming that the quality of picked clusters is equivalent. With the advantage that robotic harvesters can pick throughout the night with adequate lighting, farmers could significantly lower their need for spike labor and maintain a more constant staff throughout the year. It is our recommendation that funding for computer recognition, end effector optimum design, and motion planning be considered in the near future.

In-field Transportation

Manual harvesting requires workers to use picking baskets, bags, buckets, or plastic crates and then haul them to a general collection area. Produce that is packed in-field is generally transported using carts that are moved by hand or pulled via small tractors. If not automated, this can be a tedious, fatiguing, and time consuming task.

After visiting growers in five different states, it was determined that in-field transportation served as one of the most feasible applications of robotic technology in grape production, both economically and technologically.

Using robotic vehicles for in-field transportation of grapes offers a number of advantages. First and foremost, it significantly reduces the cost of human labor, as well as the stress and cost associating with hiring and training skilled workers. Several of the vineyard owners we met with expressed dismay at the collective age of their manual workforce. Many of their skilled laborers are older than 40 years of age and the physical toll associated with carrying heavy bins up and down the rows will lead to a labor shortage as they age. The use of robots to transport grapes from the field to a packing or shipping area could reduce, if not completely eliminate, these concerns.

Workers' wages are typically assessed based on the quantity of fruit picked in a day. Using a simple identification system (similar to a bar code) on the outside of the bin would allow workers to fill their containers, apply their identification code, and have a robotic vehicle scan the code and lift the container for transport. An integrated weight scale could record the weight and store it to a database along with the worker's id code.

Since collision avoidance is standard technology for robotic vehicles, safety concerns for vehicle and worker interactions should be minimal. Advances in programming traverse maps for autonomous vehicles means that very little new technology is required for the in-field transportation task. Development of a heavy-lift manipulator arm to lift the individual bins (estimated at 20-40 pounds) onto the transport vehicle is well within the capability of current technology.

It should be noted that a robotic vehicle could be fitted with applique kits that allow it to do a variety of tasks, such as crop monitoring and weeding during the growing season, and then be converted to an in-field transport vehicle during harvest.

TECHNOLOGY RESEARCH: EXISTING AND DEVELOPING TECHNOLOGIES

In the time since visiting the vineyards operations across the US between July 2014 and March 2016, the team has investigated the ongoing developments in precision robotics for vineyard operations. The team has found that there is a wide variety of research and development taking place in the arena of agricultural robotics, stemming from both educational institutions and private entities. The field of agricultural robotics is wide open; in fact, a January 2018 report by IDTechEx estimates that agricultural robotics will become at $35 billion industry by 2038; this includes everything from autonomous, self-driving tractors to smaller fleets of robots that can prune, weed and harvest crops.

When it comes to promoting the use of robots in vineyard operations, there are certain aspects that are a common focus of research, including weeding, crop monitoring, yield estimating, and pruning. Following is a summary of existing technologies, as well as some of the most significant research taking place in this fast-growing field.

Weeding

NAOI Technologies, based in France, has developed what they call the "first electrically driven robotic straddler to autonomously weed vineyards." According to the NAOI website, the machine, dubbed "Ted," is expected to hit the market in 2018 and can mechanically weed vineyards while aerating the soil. They also expect it to be able to complete other tasks, including de-budding (removal of unwanted growth buds), shoot thinning, spraying and collecting data as their technology development continues. The machine runs on GPS and laser guidance, and has a claimed autonomous run time of 8 to 10 hours when being used for weeding.

Another French company, Vitibot, is also working on an autonomous multipurpose vehicle that will offer mechanical weeding of vineyards. Like Ted, Vitibot's "Bakus" will eventually be a multipurpose machine and include the ability to spray. According to the Vitibot website, Bakus is expected to be commercially available in 2018.

Spraying

Through our research, we were unable to identify a fully autonomous ground vehicle whose primary function is spraying for pesticides and weeds. Several entities have these types of ground vehicles in development, but none are readily commercially available as of the timing of this report.

On the ground, a partnership between institutions and universities in Greece and Cyprus is developing SAVSAR, or Semi-Autonomous Vineyard Spraying Agricultural Robot. According to the SAVSAR website, the machine is being designed to operate in three modes: autonomous, teleoperated, or mixed. In the mixed mode, the robot will operate autonomously until it encounters a situation in which human intervention is required.

Another project in development, called GRAPE, or Ground Robot for VineyArd Monitoring and ProtEction, is a semi-autonomous, multi-functional robot that will include a spraying function that will allow growers to use pesticides and other chemicals with “honeybee precision.” According to the project’s website, GRAPE, which is being developed by project partners in the European Union, also will provide plant-level monitoring.

Finally, the company Blue River Technology, which was recently acquired by John Deere, says that its “See & Spray” technology reduces the amount of pesticides needed by 90 percent, thanks to its “intelligent” computer vision, which allows it to only spray herbicide on weeds and learns as it goes. This technology is currently being applied only toward cotton and lettuce weeding, with more crops in development.

While there are no ground robots currently available on the commercial market that offer spraying capabilities, numerous aerial vehicles (UAVs) are currently in use for crop spraying. Using light-detection methods, drones are able to target weeds for spraying more quickly and efficiently than a traditional mechanical sprayer. DroneAG, which is based in the UK, as well as Yamaha’s RMAX drone, both offer commercially available crop-spraying drones.

In May of 2016, a Napa Valley vineyard was the first site in the US to use the Yamaha RMAX for commercial crop spraying. An application of a fungicide for the prevention of powdery mildew was applied by the RMAX vehicle. Benefits cited for UAS spraying include safer and more reliable application of treatments with no soil compaction. Applications via RMAX are said to have proven faster and more efficient than current ground spray applications from four-wheelers, tractors or workers on foot. It provides growers with more flexibility and accessibility to their fields, particularly on steep hillsides. It will also decrease workers’ exposure to chemical sprays compared to manual methods of applying these chemicals.

The efficiency of drones for aerial spraying compared to manual spraying is impressive. Not only is the time to spray a given area reduced, but the physical strain on the laborers who are carrying 40 pound backpacks filled with chemicals is removed. Over the summer of 2016, an experiment was conducted at a Napa vineyard to compare delivering fungicides using the RMAX UAV and a land-based sprayer. Each vineyard was sprayed eight times at two-week intervals, with vines getting either airborne or ground-based spraying on the same days to remove variables in the experiment. While the aerial spraying showed distinct advantages on highly sloped vineyards, results on the rest of the experiment are not available online.

Pruning

Even with the use of the mechanization that is already deployed in some vineyard operations today, pruning remains one of the biggest expenses when it comes to vineyard operations. Therefore, it's no surprise that this is one of the areas targeted for automation. The use of automation may find the most acceptance in the mid to large volume producers. Wineries that focus on high priced wines will likely still rely on hand pruning to achieve optimum cane health and cluster location.

In addition to being expensive, hand pruning is a repetitive task that takes its toll on workers, resulting in fatigue and injury. Mechanization of certain tasks, such as with the V-MECH Rotary pruner, which uses optical technology to ensure cut uniformity, has alleviated some of these issues, but a fully autonomous or semi-autonomous robotic pruning system is not yet commercially available. Through research, we were not able to find any robots available on the commercial market that provide autonomous pruning. Multiple agencies/institutions do have them in development, however, including:

Vision Robotics

In 2012, Vision Robotics received a grant from the U.S. Department of Agriculture Special Research Initiative to develop an Autonomous Intelligent Grapevine Pruner, which used modeling to identify which vines or branches need to be trimmed. While the technology is still listed on Vision Robotic's website, no updates have been made in recent years as to the status of this project.

Wall-Ye France

Also from 2012 is the Wall-Ye Robot, which, when it debuted, was marketed as having the ability to prune, pick grapes, and also monitor vineyard production. The latest news featuring the pruning capability is from a November 2016 article that stated that Wall-Ye is outfitted with 6 camera sensors and is able to make a cut every 5 seconds. According to a Wall-Ye representative, the Wall-Ye is available for sale with an autonomous pruning capability that can operate continuously for 10-12 hours. The pruning metric stated on their website (http://wall-ye.com/myce_vine/index.html) is 50 plants/ hour.

Sucker Removal (AKA De-suckering)

The process of de-suckering, or the removal of some of the shoots that grow from young grape vines, is one of the most strenuous jobs a vineyard worker can have. Constant bending and standing can lead to injury; in fact, it's estimated that workers bend 3,000 to 4,000 times a day when de-suckering vines. Moreover, as with pruning, the use of manual de-suckering tools can lead to repetitive stress injuries.

There are numerous mechanical tools commercially available, including the lightweight EPAV2 battery-operated de-suckering tool by Infaco. Similar in looks to a string trimmer the EPAV2 features specialty designed flyweights that pull the sucker out right beneath the surface. Other tools that are similar in nature are readily available.

However, similar to pruning, we could not find many robotic de-suckering technologies in development. Wall-Ye, mentioned above, is said to have de-suckering capabilities, but this feature is not included on the Wall-Ye datasheet.

Crop Monitoring and Yield Estimation

Crop monitoring and yield estimating seems to be one of the most researched aspects of agricultural robotics. Traditionally, vineyard workers walk up and down the rows of vines to visually inspect plant growth and yield. Fundamentally, determining whether grapes are ready for harvesting is a task best suited to the human eye and ability to taste and, as such, is one of the most time-consuming and laborious parts of wine growing. Despite these challenges, several robotic systems are in development to help vineyards improve efficiency and increase yield.

Efficient Vineyard

One major research project taking place right now is a partnership among several universities and organizations, including Cornell, CMU, UC Davis, Penn State, Newcastle University, the USDA and the National Grape and Wine Initiative. According to its website, the goal of the project, dubbed Efficient Vineyard, is to "deliver an innovative, science-driven, and approachable precision viticulture platform to measure and manage sources of vineyard variation."

Using existing sensor technologies, the project aims to build technology that can collect spatial data on wine, juice and table grapes. Researchers want to be able to transform collected data and measurements about soil, vines and fruit into usable information to improve efficiency.

Vinbot

Described as an “all-terrain autonomous mobile robot with a set of sensors capable of capturing and analyzing vineyard images and 3D data,” Vinbot uses its “Precision Viticulture” tool and cloud computing applications to measure vineyard yield and share the information with winegrowers. A consortium of 9 European organizations, Vinbot uses open-source software and 3D range finders to navigate vineyard fields to estimate the amount of leaves, grapes and other data on the vines. This allows winegrowers to optimize production and management of their vineyards. It is still in development and is not yet commercially available. The progress of this project is unclear, as the last news item posted to the Vinbot website is from January 2017.

In addition to on-the-ground agricultural robotics, UAVs like drones are playing a significant role in the automating of crop monitoring, through the use of cameras and other sensors that can produce time-series animations more efficiently than satellite imagery.

VINEROBOT

A second consortium, including 8 partners from 4 different European countries, has another vineyard monitoring robot in development named VINEROBOT (VINEyardROBOT). Similar to Vinbot, VINEROBOT uses artificial intelligence, sensor technology and solar power to monitor plant growth and to capture data about the readiness of the fruit. The sensors are also designed to monitor water stress and grape and soil composition. As with Vinbot, the status of this project is unclear, as a “Final Meeting” for the project was posted on the VINEROBOT website in June 2017.

University of New South Wales

Researchers at the University of New South Wales, in partnership with The Australian Wine Research Institute and several other government and commercial entities, have been conducting research on multiple vineyard labor intensive tasks. This group has developed a method for generating high-resolution maps of visible vine parameters such as shoot or bunch density using low-cost cameras (e.g. GoPro and cell phone cameras). These cameras can be mounted on either manned or unmanned vehicles. They are able to avoid the use of costly GPS units by utilizing camera data to produce a geo-referenced map. Taking an early assessment of the relative yield maps allows them to be used to adjust vineyard management tasks such as trimming or canopy thinning. In an online presentation, Dr. Mark Whitty presented the results of their research in the topics of Visual Yield Estimation, Vine Water Stress identification, Bunch Maturity Sensing and Bunch Reconstruction. A request was made for an update on this research and has not been obtained at the time of this report.

Harvesting

As previously stated, self-propelled mechanical grape harvesters, which vibrate the vines to release ripe grapes, have been in use for decades. One of the main complaints about mechanical harvesters, however, is that they often collect what is known as “MOG,” or material other than grapes, along with the fruit. Because these machines do not inspect for quality, this unwanted material can include rotted grapes, leaves, stems and seeds.

To match the technique and ability of human labor, fully autonomous grape harvesters would need to employ a collaboration of vision processing, manipulation and deep learning techniques. The vision processing system would need to distinguish between clusters of ripe and unripe fruit, and direct the manipulator to the appropriate stem for cutting. The system would need to include a mechanism to catch the cluster once cut. Some of the groups working on robotic harvesting are described below.

CROPS (Clever Robots for Crops)

CROPS is European consortium of 13 private companies and universities worked together to design a robotic harvester, which also incorporated “intelligent spraying” processes. Coordinated by Wageningen UR Greenhouse Horticulture in The Netherlands, program objectives included multispectral imaging for the detection, classification and localization of fruits to be harvested and of crop diseases to be sprayed. The technology utilized imaging and fluorescence to determine fruit ripeness. End effector prototypes that included grippers, precision sprayers and canopy sprayers were also developed and tested in field experiments, and ripeness learning systems were tested on apples and sweet peppers. The program was in progress between 2010 and 2014. The latest news available on the CROPS website is from August of 2016.

Abundant Robotics

Although currently being tested on apple picking, in May of 2017, Abundant Robotics received $10 million in funding from Google Ventures to research and develop its autonomous fruit harvesting technology. The company, which is based in California, spun out of SRI International.

It began working on the apple-picking project five years ago. The technology utilizes computer vision and a vacuum system, instead of end effectors, to gently remove the fruit from the tree. The company's robots are designed to work 24 hours a day, even in darkness. According to recent reports, the company hopes to eventually be able to apply the technology for other crops as well.

Sorting

One of the most laborious tasks during the harvesting process is the sorting of grapes by quality and ripeness. Since mechanical harvesters can't discern healthy grapes from those that may be unripe or rotten, sorting is essential to ensure a high-quality final product. Grape-sorting technology has been in use for years; yet, as technology advances, so does the ability for optical grape sorters to become more accurate. Two of the grape sorting machines on the market are described below. A report published in October 2013 stated that eight wineries were using high speed optical sorters at that time.

GrapeSort Optical Sorter

Wine experts from Geisenheim University in Germany, in conjunction with other universities and private companies, researched and developed automated grape-sorting technology, which uses a high-speed camera to determine the sugar content in an individual grape. The technology allows vineyards to separate MOG like leaves, twigs and bugs after the harvest, and also allows growers to separate grapes according to quality. The technology, dubbed the GrapeSort Optical Sorter, is a venture between the university, Fraunhofer Institute and Arbruster Kelteri-Technologie and is being manufactured by Rotovib. It is currently available on the Rotovib website.

Bucher vaslin Delta Oscillys

Like the GrapeSort Optical Sorter, the Delta Oscillys relies on high-speed cameras, as well as vibration and precision airflow, to separate grapes from MOG.. The vintner can program images of "perfect" grapes and vision system compares each grape on the conveyer belt to the ideal image. A small puff of air removes any grapes or MOG that do not match the programmed images. This technology is currently available for commercial use.

NOTE: Although not considered robotic technology, numerous other optical sorters from other manufacturers are also widely available, including the VitiSort Wine Grape Sorter by Key Technology, which is based in Washington state.

REFERENCES

Ackerman, E. (2017, September 11). Autonomous Robots Plant, Tend, and Harvest Entire Crop of Barley. Retrieved March 2, 2018, from https://spectrum.ieee.org/automaton/robotics/industrial-robots/autonomous-robots-plant-tend-and-harvest-entire-crop-of-barleyAnderson, C. (2015, February 03). How Drones Came to Your Local Farm. Retrieved March 28, 2018, from https://www.technologyreview.com/s/526491/agricultural-drones/

Belton, P. (2016, November 25). In the future, will farming be fully automated? Retrieved March 20, 2018, from http://www.bbc.com/news/business-38089984

Berner, B., & Chojnacki, J. (2017). Use of Drones in Crop Protection. *Farm Machinery and Processes Management in Sustainable Agriculture, IX International Scientific Symposium*. doi:10.24326/fmpmsa.2017.9

Canopy Management - Shoot Thinning and Positioning. (n.d.). Retrieved March 28, 2018, from http://extension.umd.edu/learn/canopy-management-shoot-thinning-and-positioning

Carbone, Carlos & Garibaldi, Oscar & Kurt, Zohre. (2018). Swarm Robotics as a Solution to Crops Inspection for Precision Agriculture. KnE Engineering. 3. 552. 10.18502/keg.v3i1.1459.

Cline, H. (2010, August 25). Mechanical vine pruning dramatically reduces costs. Retrieved March 2, 2018, from http://www.westernfarmpress.com/mechanical-vine-pruning-dramatically-reduces-costs

Fast and comfortable vineyard suckering. (2015, April 25). Retrieved Feb. 22, 2018, from https://infaco-usa-blog.com/2015/04/24/fast-and-comfortable-vineyard-suckering/

Fundamentals of Canopy Management. (n.d.). Retrieved March 9, 2018, from http://articles.extension.org/pages/33059/fundamentals-of-canopy-management

Ghaffarzadeh, K. (2018, January 23). Agricultural Robots and Drones 2018-2038: Technologies, Markets and Players. Retrieved March 14, 2018, from https://www.idtechex.com/research/reports/agricultural-robots-and-drones-2018-2038-technologies-markets-and-players-000578.asp

Ghaffarzadeh, K. (2018, January 26). Agricultural robots and drones could become a $35Bn industry by 2038? Retrieved March 23, 2018, from https://www.roboticsresear.ch/articles/13509/agricultural-robots-and-drones-could-become-a-45bn-industry-by-2038?stv1=1:353205:12402

Gonzalez, C. (2018, January 26). Farm Robotics are Taking a Giant Automated Leap Forward. Retrieved March 2, 2018, from http://www.machinedesign.com/motion-control/farm-robotics-are-taking-giant-automated-leap-forward

Ground Robot for Vineyard Monitoring and Protection (GRAPE). (n.d.). Retrieved March 2, 2018, from http://www.grape-project.eu/

Home. (n.d.). Retrieved February 23, 2018, from https://www.efficientvineyard.com/

How a Robot Can Sort 2 Tons of Grapes in 12 Minutes. (2016, May 03). Retrieved March 13, 2018, from https://modernfarmer.com/2014/01/robot-can-find-2-tons-perfect-grapes-12-minutes/

Is your orchard robot ready? - Video. (n.d.). Retrieved March 2, 2018, from http://www.goodfruit.com/is-your-orchard-robot-ready-video/

Kolodny, L. (2017, May 03). Abundant Robotics rakes in $10 million for apple harvesting robots. Retrieved March 19, 2018, from https://techcrunch.com/2017/05/03/abundant-robotics-rakes-in-10-million-for-apple-harvesting-robots/

ksbwtv. "Monterey County Vineyard Using Robots to Harvest Grapes." *YouTube*, YouTube, 24 May 2017, www.youtube.com/watch?v=b9lPQO_gJSo.

Krishna, K. R. (2016). *Push button agriculture: Robotics, drones, satellite-guided soil and crop management*. Oakville, ON, Canada: Apple Academic Press.

Mazur, M. (2016, July 22). Six Ways Drones Are Revolutionizing Agriculture. Retrieved March 19, 2018, from https://www.technologyreview.com/s/601935/six-ways-drones-are-revolutionizing-agriculture/

Mueller-Sim, T., Jenkins, M., Abel, J., & Kantor, G. (2017). The Robotanist: A ground-based agricultural robot for high-throughput crop phenotyping. *2017 IEEE International Conference on Robotics and Automation (ICRA)*. doi:10.1109/icra.2017.7989418

Navigation Strategies for a Vineyard Robot. (2015). *2015 ASABE International Meeting*. doi:10.13031/aim.20152189750

Northern NY Grape Management Update. (n.d.). Retrieved March 2, 2018, from http://blogs.cornell.edu/nnygrapeupdate/2013/06/13/vsp-moving-catch-wires/

Ohioline. (2014, January 22). Retrieved March 2, 2018, from https://ohioline.osu.edu/factsheet/HYG-1436

Pre-Pruning in the Vineyard: Disease Prevention and Vine Life Extension. (2015, January 16). Retrieved March 2, 2018, from https://bottletalks.wordpress.com/2015/01/08/pre-pruning-in-the-vineyard-disease-prevention-and-vine-life-extension/

Precision viticulture: Digital technologies for monitoring and management of the vineyards. (2018, March 02). Retrieved March 2, 2018, from http://feelgrid.com/web/precision-viticulture-digital-technologies-for-monitoring-and-management-of-the-vineyards/

Pruning vs Pre-pruning. (n.d.). Retrieved March 2, 2018, from http://napavintners.blogspot.com/2012/03/pruning-vs-pre-pruning.html

Quackenbush, Jeff "North Coast vineyards see more drone use as agriculture market soars". *North Bay Business Times*, January 10, 2017, http://www.northbaybusinessjournal.com/northbay/sonomacounty/6240979-181/vineyard-drones-uav-agriculture-aerial-imaging

Smart Robots for Picking Fruit. (n.d.). Retrieved March 23, 2018, from https://www.asme.org/engineering-topics/articles/robotics/smart-robots-for-picking-fruit

Spengler, J. (n.d.). Tried, True and NEW Vineyard Equipment. Retrieved March 2, 2018, from http://thegrapevinemagazine.net/article/tried/

Ted, the vineyard weeding robot. (2017, January 25). Retrieved March 2, 2018, from https://www.youtube.com/watch?v=uGlo7woEhQo

The Future of Winmaking is in High-Tech Robotics (2013, October 8). Retrieved March 22, 2018, from https://www.youtube.com/watch?v=okHzwTbydXk

Trellis Systems: Vertical Shoot Position. (n.d.). Retrieved March 2, 2018, from http://articles.extension.org/pages/31127/trellis-systems:-vertical-shoot-position

VINBOT. (2014, May 26). Retrieved March 2, 2018, from http://vinbot.eu/

Vineyard Canopy Management. (n.d.). Retrieved March 2, 2018, from http://www.wine-grape-growing.com/wine_grape_growing/vineyard_canopy_management/vineyard_canopy_management_techniques.htm

Wall-YE Softwares & Robots. (n.d.). Retrieved February 23, 2018, from http://wall-ye.com/index.html

Walsh Vineyards Management blog: http://wvmgmt.com/blog/2014/1/16/pruning-part-one-pre-pruning

Whitty, Mark "Practical and Precise Perception for Vineyards", University of New South Wales (UNSW), retrieved March 22, 2018, from https://recordings.join.me/VRsNT5dadkiMOuAIe7yCnQ

Wilson, Andy. "Vision and Robots Team up for Wine Production." *Vision Systems Design*, 11 Apr. 2016, www.vision-systems.com/articles/print/volume-21/issue-4/features/vision-and-robots-team-up-for-wine-production.html.

"Yield Monitoring in Bulk Juice Grapes." *Cornell Cooperative Extension*, chautauqua.cce.cornell.edu/news/yield-monitoring-in-bulk-juice-grapes.

Yune, Howard "Napa County wineyards host pioneering drone tests", Napa Valley Register, September 1, 2016, http://napavalleyregister.com/news/local/napa-county-vineyards-host-pioneering-drone-tests/article_9fe9e60a-28ff-5d36-806b-68439290a572.html