**FINAL REPORT** **YEAR**: 3 of 3

**WTFRC Project Number: TR 11-100**

**Project Title**: Intelligent bin-dog system for tree fruit production (Phase II)


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**Cooperators**: WA Producers, Yakima Valley Orchards

**Total Project Request:** **Year 1:** 99,397 **Year 2:** 69,454 Year 3: No Cost Extension

**Other funding sources**

**(***None)*

**Budget 1**

**Organization Name:** WA State University **Contract Administrator: Carrie Johnston**

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| **Item** | **2011-12** | **2012-13** | **2013-14** |
|---|---|---|---|
| **Salaries**[1] | 65,352 | 47,966 | -- |
| **Benefits** | 16,045 | 9,488 | -- |
| **Wages** | -- | -- | -- |
| **Benefits** | -- | -- | -- |
| **Equipment**[2] | 7,000 | -- | -- |
| **Supplies & Fabrication Costs**[3] | 5,000 | 6,000 | -- |
| **Travel** (Zhang)[4] | 2,000 | 2,000 | -- |
| **Travel** (Lewis)[4] | 3,000 | 3,000 | -- |
| **Miscellaneous**[5] | 1,000 | 1,000 | -- |
| | | | |
| **Total** | 99,397 | 69,454 | 0 |

**Footnotes:** [1] one Post-doctoral research associate (12 months) and one Ph.D. graduate student (12 months) for yr-1; one Post-doctoral research associate (12 months) for yr-2; [2] Budget for purchasing an existing bin-carrier platform; [3] Budget for fabricating bin-dog prototypes (yr-1 for the research prototype and yr-2 for the demonstration prototype (including NAPA parts); [4] Budget for travel will cover the expenses for research personnel traveling to experiment sites for conducting project activities; [5] A small miscellaneous budget is for all other project related expenses.

## OBJECTIVES

This project is in the second phase of intelligent bin-dog concept research. The primary goal of this phase was to develop a research prototype of a self-propelled "bin-dog" usable in typical PNW tree fruit orchards. This "bin-dog" research prototype should have the following essential functionalities to be considered a success of this research: (1) capable of traveling in typical PNW tree fruit orchards using manually maneuvered electronic control systems; and (2) capable of carrying and placing an empty bin at target locations in harvesting zone, then picking and carrying a full bin away from the harvesting zone in the same run to support safer and more effective harvesting. One workable research prototype has been designed, fabricated and tested in both research and commercial orchards in Yakima Valley in 2012-13 (Year 2). Aimed at improving some identified limitations on the first research prototype from Year 2 field tests, a no-cost extension was requested and proved to address those issues through design, fabricate and test of the second research prototype. The following specific project activities have been conducted in this no-cost extension period:

1. Based on the identified limitations of prototype-one (as reported in 2013 Spring Progress Report), a prototype modification plan was specified, and a prototype-two was designed and fabricated. The limitations and defects being identified and to be removed included insufficient power, steering with limited controllability, unreliable bin-loading system, branch hitting due to the frame height and uneven traction force on wheels. Similar to prototype-one, prototype-two was also built using off-the-shelf components (both mechanical and electrical components); and
2. Conducted both laboratory and field tests to validate the improvements achieved from prototype-two, confirm that the identified limitations and defects were removed or at least reduced, and identify new challenges, if any, of the new prototype from testing in both research and commercial orchards.

In summary, this project was planned to develop and prove a concept of using a "bin-dog" to manage bins within modern orchard environment, and to validate its critical functionalities and assess its usability in PNW tree fruit orchards. To accomplish the goal, two manually maneuvered and electronically controlled "bin-dog" research prototypes have been fabricated and tested in both laboratory and research/commercial orchards in PNW region. Test results verified that both prototypes could fulfil the basic functionalities and the second prototype has removed a few limitations or defects that were identified from the field test of the first prototype, such as unreliable bin-loading system, branch hitting due to the frame height, and uneven and/or insufficient traction force, or at least partially removed, such as insufficient power, steering with limited controllability. This project provided us the necessary resources to explore an innovative concept, and to obtain the essential preliminary results adequately supporting our efforts to seek federal funds to complete the full-scale research and development. One full scale research proposal, collaborating with engineers, computer scientists and robot scientists from WSU and OSU, has been developed and submitted to the National Robotics Research Initiative for funding.

## SIGNIFICANT ACCOMPLISHMENTS

### Design of Prototype-Two of the "Bin-Dog"

In this extended research period, a new "bin-dog" prototype has been designed and fabricated (as shown in Figure 1) to provide the required critical functionalities, including orchard traversing, bin handling, and to overcome the limitations identified on prototype-one, such as insufficient power, poor steering controllability, unreliable bin-loading system, branch hitting due to the frame height and uneven and/or insufficient traction force. The mechanical structure of this new prototype consists of four subsystems; driving, steering, bin lifting and frame leveling.

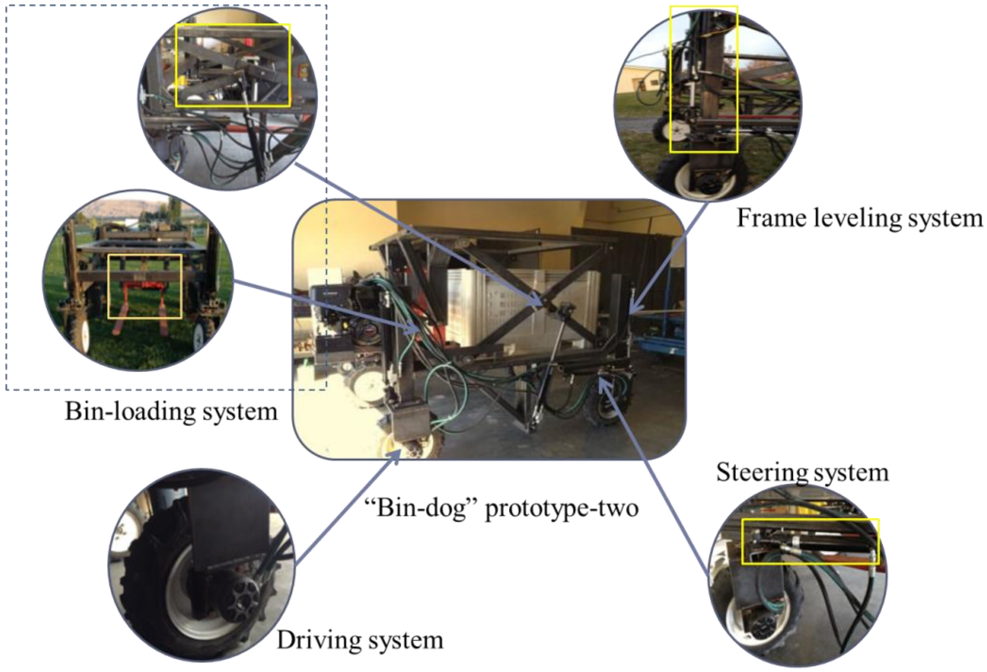
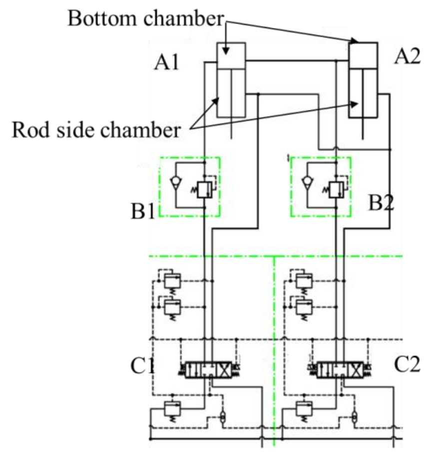



**Figure 1 Fabricated "bin-dog" prototype-two**

<u>*Design of the driving system addressing insufficient power and poor traction force*</u>

Insufficient power has been identified as a limitation for "bin-dog" prototype-one which was an electrical two-wheel-drive system driven using two 0.75 kW (1.0 hp) DC motors. To solve this problem, an electro-hydraulic driving system with a four-wheel-drive mechanism and an independent-wheel-tracking-control mechanism were designed for this new prototype. Each of the four independently-driven wheels was actuated using a hydraulic motor. To get either a higher speed or a higher torque, the motor arrangement could be switched between serial (for higher speed) and parallel (for higher torque) arrangement by changing the hose connection between motors. To address one of the major defects identified on prototype-one, the poor maneuverability of the "bin-dog" caused by poor traction force due to inability of all four wheels firmly engaging on uneven surface in orchards, an innovative hydraulic wheel-ground engaging mechanism has been designed (as illustrated in Figure 2) to gain this capability. In this design, the rod side chambers of the frame leveling cylinders on the front wheels are connected together as well as those of the bottom chambers. When driving on flat surface, the fluid in the four chambers is under an equilibrium status. Once a front wheel disengages from the ground due to uneven ground surface, pressure of rod side chamber of that wheel will be quickly reduced which will break the equilibrium. Then the hydraulic fluid in other chambers will push down the rod of the wheel until it engages to the ground again or until the rod extends to its limit. Similarly, when a front wheel runs over a bump, the imbalance of pressures will also adjust the extending lengths of rods on the two front wheels until equilibrium is established. Thus when within its workable range, the mechanism guarantees all four wheels will be firmly engaged on the ground. The functionality and control of frame leveling will be explained in a later section.




A1, A2: Frame leveling cylinders of front wheels
B1, B2: Sequence valves
C1, C2: Proportional valves

**Figure 2 Hydraulic schematic of an active frame leveling and passive wheel-ground engaging system**

*Design of the steering system to improve steering maneuverability*

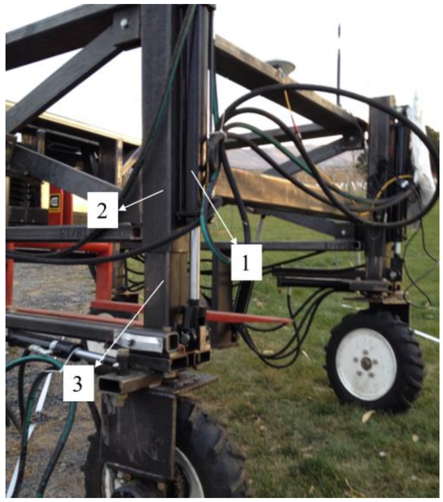
To improve the maneuverability of the "bin-dog" in confined orchard row space, one of the major identified limitations of prototype-one, a "programmable two-wheel steering control system" was developed which coordinately controls the steering of two individually actuated wheels. To steer an individually actuated wheel, an electronically controlled hydraulic system was used to extend or retract a linear hydraulic cylinder to get desired steering angles. The control system allows the operator to control whether those two individually actuated wheels turn synchronously or independently. In this new design, adding only control software without changing the mechanical structure and hydraulic systems design, noticeably improved the maneuverability of the "bin-dog". A feedback control scheme will be required to further improve the steering accuracy with minimal corrections. In addition, as the coordinate control scheme could improve both improve the maneuverability and steering accuracy, the field tests indicated that it was difficult, if not impossible, to achieve satisfactory maneuverability and steering accuracy within a very confined space between tree-rows using a traditional two-front-wheel steering (namely Ackermann steering), a common design for most field mobile equipment. An all-wheel steering mechanism may be essential for obtaining a satisfactory maneuverability in such a working environment.

*Design of a new bin-loading system for improving the reliability of the pick and carry function*

As the bin-loading system designed for prototype-one could not effectively and reliably pick and carry a bin in the orchard environment due to the limitation of the picking-finger mechanism, a forklift-type bin loading mechanism supported by a hydraulically actuated scissors-structured lifting mechanism was used to gain an effective and reliable bin handling capability under both light and heavy load conditions. In this design, two cylinders symmetrically installed on both sides of the scissors structure, and flow divider was used to ensure the two cylinders extend and/or retract at the same pace to effectively raise or lower a bin while the bin-dog is in motion. Field tests validated that this mechanism could reliably handle the bins, with some room to improve in the effectiveness.

*Frame leveling system to further improve the maneuverability and safety*

The frame leveling system is a new feature for "bin-dog" prototype-two. The frame leveling system serves the three purposes of allowing "bin-dog" to adjust (1) its frame vertically in parallel to the trees to gain the best accessibility between tree-rows; (2) the center of gravity increasing traction force on “steering” wheel when traveling uphill; and (3) the pose of bin on the fork avoiding weight shifting-induced machine rollover. As depicted in Figure 3, a hydraulically controlled sliding structure (consists of leveling cylinder, outer sliding tube and inner sliding tube) was designed to adjust the height from the frame. Using four individually controlled frame leveling control mechanisms, this “bin-dog” prototype could level the bin at 15° heading/tail slope and 15° side slope. A wider range of leveling ability could be achieved through system reconfiguration (either choosing longer cylinders or redesigning the structure). Currently this leveling system is controlled manually using an electro-hydraulic implementing system.




In the figure, 1: Leveling cylinder; 2: Outer sliding tube; 3: Inner sliding tube

**Figure 3 Mechanical design of the bin leveling system (on one wheel)**

### Design of power and maneuvering system

To solve the insufficient power problem of prototype-one, the new prototype was powered using a 9.7 kW (13.0 hp) gas engine, with all the implementing systems (driving, steering, loading and leveling) driven by electronically controlled hydraulic systems via 8 bidirectional proportional control valves. Figure 4 shows the block diagram of this electro-hydraulic control system. In performing the manual maneuvering of this “bin-dog” research prototype, the operator inputs an implementing command via an electronic control panel, which will generate wireless signals and send those signals to corresponding electro-hydraulic control valves for performing the operation.

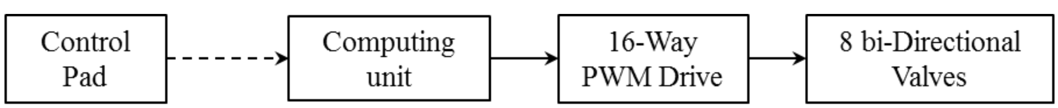



**Figure 4 Block diagram of electrical maneuvering system**

To actuate all 8 bidirectional control valves, a total of 16 control signals needed to be generated, distributed and converted into PWM (Pulse Width Modulation) format. To accomplish this complex signal processing and at the same time avoid premature design of a complicated controller, a simple 12-key control panel (Figure 5) was used as the input signal generator for the controller. A set of key combinations, representing different control commands will be sent to a custom built control box for implementation. Table 1 lists the definition of the key combinations for different control functions.

**Table 1. Key combinations for control functions**

| Key | Function | Key | Function |
|---|---|---|---|

| (Page 1) | | (Page 2) | |
|---|---|---|---|
| 1, 2 | Forward/Backward | 1 , 2 | Frame Leveling Cylinder 1 extending/Retracting |
| 3, 4 | Coordinated Steering Left/Right Turn | | |
| 5, 6 | Fork Lifting/Lowering | 3, 4 | Frame Leveling Cylinder 2 extending/Retracting |
| 7, 8 | Left Wheel Left/Right Turn | | |
| 9, 10 | Right Wheel Left/Right Turn | 5, 6 | Frame Leveling Cylinder 3, 4 extending/Retracting (Passive Suspension Adjustment) |
| 11 | Switch Page | | |
| 12 | Stop all Functions | 12 | Stop all Functions |

**Figure 5 12-key control panel**

**Laboratory Functionality Tests and Field Validation Tests**

To test the designed functionalities and validate the accomplished improvements on prototype-two, a set of laboratory functionality tests and another set of field validation tests were conducted both in CPAAS laboratory and in both research and commercial orchards near Prosser.

*Maneuverability tests*

The “bin-dog” steering control system was an open-loop system. A steering angle was achieved by setting the start time and stop time of the steering. As a few factors, such as internal and external resistances, would affect the response speed of the electrohydraulic steering system, the evaluation of control performance of “bin-dog” steering included the response time (time elapsed from command being sent to the initiation of according action) and time used to complete a steering action.

The time for the steering system responding to a steering command was 370 ms on average. Under current control system configuration, when the temperature of hydraulic fluid was 22°C (71°F), it took both left and right steering wheel 2 s to turn from the neutral position (0°) to the leftmost position (40°) or the rightmost position (-40°) on paved road.

An additional maneuvering test was set to test the driving and steering performance of prototype-two within confined space and on different ground surfaces. To create a confined space similar to the tree lane configurations in orchards, ribbons were used to set the boundaries of the driving path, as illustrated in Figure 6. During the test, the operator manually drove the “bin-dog” forward from point A, took a turn and stopped at point B. At point B, “bin-dog” started backward, took a turn and stopped at point C. All the actions were completed within the boundaries. Once “bin-dog" touched boundary, it would be stopped and driven back in the driving path. The locations of boundaries were all recorded using a RTK GPS. Then the GPS was mounted on the center line of "bin-dog" which recorded location and time information of "bin-dog" during tests. Three sets of maneuvering tests were carried out on paved road, on lawn and on side slope, all in IAREC campus.

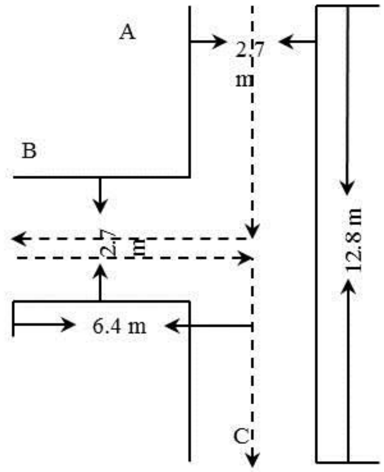



**Figure 6 Laboratory driving test setup and test pathway configuration (unit: m)**

Figure 7 shows the result in LTP (Local Tangent Plane) coordinates obtained from one of the maneuvering tests conducted on the lawn test pathway. Point A and C were selected so that the driving paths of forward and backward processes in all tests were the same. In forward motion the "bin-dog" was in a front-wheel-steering mode, and in backward motion it was in a rear-wheel-steering mode. As the recorded trajectory showed being smoother when driving forward when compared to driving backward, it indicated that front-wheel-steering provided better trajectory controllability than rear-wheel-steering on this "bin-dog" while maneuvered manually.

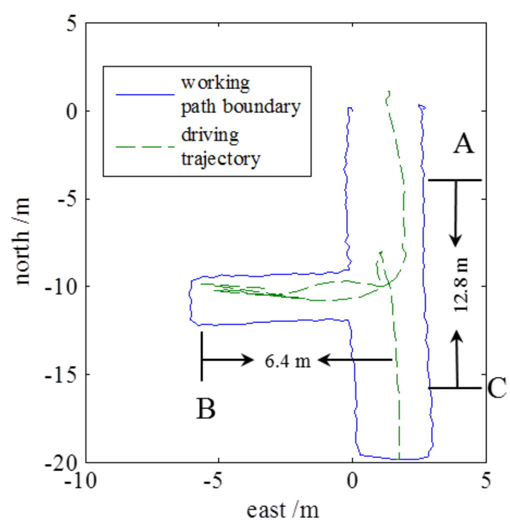



**Figure 7 Working path boundary and working trajectory presented in LTP coordinates**

To further compare the maneuvering performance of different driving modes (front-wheel steering from A to B, rear-wheel steering driving from B to C) and on different ground types (paved road, lawn and slope), equation (1) provides an additional measure of the "bin-dog" maneuverability.

$$\text{Maneuvering effective measure} = \frac{100}{t * \sum_i^n e / n} \quad (1)$$

In this measure, $t$ is the time used to complete a drive path (A to B or B to C), $n$ is total number of GPS sample points for the location of "bin-dog" being recorded during the driving and $e$ is the distance between a GPS recorded trajectory point and the center line of the ideal driving path. As the operator tried to locate the center of "bin-dog" along the center during the test, $\sum_i^n e / n$ could represent the average position error for the driving. Thus if an operation in a driving has a higher maneuvering effective measure value, as the patterns and lengths of the two driving paths are the same, it means the driving either uses less time or the average error is lower, and it will be regarded that the operator has a better driving performance in that driving. Table 3 lists the performance data obtained from 9 test runs.

**Table 3. Maneuvering effective measure**

| | Maneuvering Effective Measure ($s^{-1}\cdot m^{-1}$) | |
|---|---|---|
| | Front-wheel steering (A to B) | Rear-wheel steering (B to C) |
| Paved road | 9.2 | 3.6 |
| Lawn | 10.9 | 3.7 |
| Slope | 8.2 | 4.7 |

For the maneuvering effective measures on the 3 different ground surfaces, no large difference could be observed. It shows that the operator had stable maneuvering performances driving "bin-dog" on different ground types. But for all the 3 sets of tests, maneuvering effective measures of front-wheel steering were 142% higher than that of rear-wheel steering on average. It means that an operator could maneuver the "bin-dog" better using front-wheel steering in confined space than rear-wheel steering.

*Speed test*

In order to validate the drivability of prototype-two "bin-dog" in orchard environment, a speed test was set to test prototype-two in Yakima Valley orchards with fruiting wall tree architecture. The testing lanes were roughly 200 m long and were about 2.2 m wide. A GPS receiver was used to record the trajectories of "bin-dog" during the tests. The result showed that it took "bin-dog" 446 s at an average speed of 0.5 m/s to pass through those lanes, with a highest speed being recoded at 1.1 m/s.

To further test the drivability of "bin-dog", two supplemental tests were conducted on lawn in WSU station in Prosser. In the tests, "bin-dog" carried a light load and was driven to its highest speed. The locations of "bin-dog" were recorded using GPS. In the tests, "bin-dog" could drive up to 1.2 m/s on flat surface on lawn while the highest speed dropped to 0.9 m/s when driving on 15° slope on lawn.

*Bin handling test*

The bin transportation function is one of the core functions of the "bin-dog". To validate its go-over-the-bin capability and effectiveness within the confined space, a set of field tests was conducted within actual tree lanes in Yakima Valley commercial orchards. To test it under the worst case scenario, all those tests were conducted in "Y" trellis orchards with between tree-row lane spacing of 3.0 m. An empty bin was firstly placed at about 15 m away behind a target bin, then the "bin-dog" came back to pick the target bin and carry it away from the harvesting zone. The time used for each step, including loading an empty bin, driving to the harvest zone, going over the target bin, placing the empty bin, coming back to load the target bin, and carrying the target bin back to the loading area, was recorded. Results showed that it normally took about 4 s to load an empty bin, 10 s to lift an empty bin high enough to pass a target bin, and between 10-13 s to go-over the target bin depending on the space left between the tree-rows and the bin on both sides.  The time needed traveling to the target bin and back the loading area was very much determined by the distance from the bin loading was to the target bin.

All those tests were manually controlled using an aforementioned 12-key control panel. From this series of field tests, it was found the maneuvering of "bin-dog" under the rear-wheel-steering mode is very much operator's skill related as the operator's sight was blocked when manually maneuvered from behind. An automated guidance of the "bin-dog" could be the solution to remove this obstacle.

## DISCUSSION

### Accomplished Improvements and Identified Additional Problems

Prototype-two was designed to remove or improve the limitations/defects identified on prototype-one through modifications on four major subsystems. Obtained test results verified that the new prototype had successfully removed some of the limitations/defects and improved a few others. It also revealed a few new problems.

*Adequate driving power for a "bin-dog"*

One major identified limitation of prototype-one was the insufficient power using two 0.75 kW (1.0 hp) DC motors to drive two wheels, and one 1.4 kW (1.9 hp) DC motor to drive the lifting system. To find out an adequate range of power requirement for all subsystems of a fully functional "bin-dog", prototype-two was powered by a 9.7 kW (13.0 hp) gas engine, which used to drive a 1.4 L/s (22.2 GPM) at 3000 rpm hydraulic power unit. This hydraulic unit provides hydraulic power to 4 hydraulic motors mounted on each of the four wheels reconfigurable for getting a higher speed or a higher torque through switching motor connections in a 2-motor serial (for higher speed) mode and an all motor parallel (for higher torque) mode. The hydraulic power unit will also provide hydraulic power to actuate the steering, bin lifting and frame leveling systems when needed. In the speed tests, prototype-two was capable of driving at 0.9 m/s speed on a 15° slope on lawn. Also when testing in Yakima Valley commercial orchards, prototype-two could get to a highest speed of 1.2 m/s under a light load compared to 0.8 m/s of prototype-one. If a higher speed and/or a heavier load were required, a higher power range would be needed. A method for configuring the adequate power range to design such a "bin-dog" was identified based on the lessons learned from this design process using the following equations.

$$Pressure = \frac{r\pi(Mgsin\theta + \mu_r Mgcos\theta)}{2a} \quad (N/m^2) \qquad (2)$$

$$Flow\ rate = \frac{120va}{\pi r} \quad (m^3/s) \qquad (3)$$

$$Engine\ power = \frac{Pressure \cdot Flow\ rate}{efficiency} = \frac{60v(gsin\theta + \mu Mgcos\theta)}{\mu_e} \quad (W) \qquad (4)$$

In which $r$ is wheel radius, $\theta$ is the angle of the slope, $a$ is the displacement of the hydraulic motor, $\mu_r$ is coefficient of rolling resistance, $M$ is the mass of "bin-dog", $v$ is the desired maximum speed of "bin-dog" and overall efficiency is $\mu_e$.

*Steering with limited controllability*

To improve the steering performance of prototype-one which used two controlled driven-steering wheels and two uncontrolled swivel rear wheels to steer the vehicle, prototype-two made the two rear wheels fixed and made the platform four-wheel-driven (namely a standard Ackermann steering design for mobile equipment). After the modification, operator could gain much more controllability in steering the "bin-dog". Adding the coordinating control scheme to harmonize the turning of two independently actuated steering wheels had further improved the maneuverability of prototype-two in handling a bin. As validated in bin handling tests, the improved coordinating control scheme helped to reduce the average maneuvering time of loading a bin from 13 s to 4 s, and go over a target bin from 13 s to 12 s. The limited improvement on go-over the target bin was mainly attributing to (1) blocking the view of operator during the manual control which could be removed or improved by using a sensor-navigated automated guidance for this operation; (2) a large turning radius requirement of Ackermann steering system which could be improved by changing the steering mechanism to an all-wheel steering.

*Unreliable bin-loading system*

To improve the unreliable and very slow bin loading on prototype-one, a forklift-type bin loading system actuated using a scissors-structure hydraulic lifting system replaced the original pulley driven winch bin-lifting system. This new design worked satisfactorily on prototype-two in terms of both the reliability and efficiency in all laboratory and field tests.

*Weight distribution and center of gravity*

One new problem found on prototype-two from field tests was that its center of gravity was located in its rear part of the frame, which would lead to an insufficient traction on front steering wheels when traveling uphill on a big slope. Frame leveling system would allow prototype-two to move its center of gravity toward front wheels by extending the frame leveling cylinders on rear wheels. However, to completely remove this problem, some carefully calculated weight balance modifications are strongly recommended in design a product version of “bin-dog”.

*Poor response of steering control caused by uneven traction force on wheels*

To remove the defect of large slippage or poor response in steering identified on prototype-one, attributed to insufficient, or even no traction force on one of the four wheels while traveling on uneven ground surface, prototype-two has adopted a hydraulically actuated passive wheel-ground engaging system. While it worked well on ground with limited degree of unevenness, this wheel-ground engaging system was unable to respond quickly enough on really rough surface. Under such situations, some poor responses of steering control would frequently occur due to the imbalanced traction on four wheels. Some further improvement for obtaining more prompt response on traction force control via wheel-ground engaging would be needed.

*Improved possibility of hitting branches by lowering the frame height*

The height of prototype-one is 2.10 m which was about the height of two bins. It often hit the branches when traversing in “Y” trellis orchards. Prototype-two used a collapsible scissors structure which could reduce the “bin-dog” outer frame height to 1.50 m at all the time, and resulted in a narrow inner frame (about 0.10 m narrower than the outer frame) when the lifted bin was at its highest position (2.10 m during over-the-bin operation). This design has effectively reduced the possibility of the “bin-dog” hitting branches of “Y” trellised trees.

**Executive Summary**

During this no-cost extension period, a new research prototype of “bin-dog” has been designed, fabricated and tested in both laboratory and research/commercial orchard environments. Some of identified limitations/defects identified from prototype-one, such as slow and unreliable bin loading, poor in orchard reversibility due to prototype frame height and uneven and/or insufficient traction force have been removed, and some limitations/defects, such as insufficient power, poor steering control responses been improved. The maneuverability of newly developed prototype-two was tested under various scenarios, from paved road, lawn to commercial orchards with heading/tail or side slopes, and fairly consistent maneuverability performances was observed from those tests. However, when an operator manually maneuvered the prototype-two “bin-dog” implemented by a standard Ackermann steering mechanism, it showed a 142% higher maneuvering effectiveness measure value in forward motion (in front-wheel-steering mode) than in backward motion (in rear-wheel-steering mode). This performance difference could be attributed to the requirement of this mechanism of having a large turning radius and the confined space between the tree rows could not offer sufficient space, and to poor visibility when steering the “bin-dog” while in backward motion. In the bin handling performance test, the new prototype reduced the bin loading time from 12 s to 4 s, mainly attributed to be improved reliability in loading the bin. However, it still took 12 s to guide the new “bin-dog” to carry an empty bin over a target bin compared to 13 s for the old prototype because the new prototype was still maneuvered manually by a human operator using a remote controller, which relied on a good observation of the clearance between the “bin-dog” and the trees/filled bin. In addition, the standard Ackermann steering mechanism did show its limitation of needing a large space to be maneuvered effectively which did not exist in this confined environment. An active four-wheel steering mechanism is strongly recommended for such equipment in future designs.