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Dynamic Modeling Framework to Predict Instantaneous Status of a Tractor-Dolly System

Collin Stewart Davenport

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By

Collin Davenport

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Dynamic modeling framework to predict instantaneous status

of a tractor-dolly system

By

Collin Davenport

Approved:

Yucheng Liu
(Major Professor / Graduate Coordinator)

Michael Mazzola
(Committee Member)

John E. Ball
(Committee Member)

Jason M. Keith
Dean
Bagley College of Engineering

Name: Collin Davenport

Date of Degree: May 5, 2017

Institution: Mississippi State University

Major Field: Mechanical Engineering

Major Professor: Yucheng Liu

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Candidate for Degree of Master of Science

A dynamic modeling framework was established to predict the position and alignment (turning angle) of a tractor-dolly towing system receiving different driver inputs. This framework consists of three primary components: (1) a state space model to determine position and velocity of the system through Newton's second law; (2) a model that transfers angular acceleration through each successive towed vehicle; and (3) a polygon model to draw an instantaneous shape of the vehicle representing its location and alignment. Input parameters of this model include initial conditions of the system, real time location of a reference point that can be determined through a beacon and radar system, and instantaneous accelerations, which come from driver maneuvers found on a data collecting system installed on the tractor. The purpose is to create an output that presents the position of the dolly vehicles with reference to the tractor at any time point.

DEDICATION

This thesis is dedicated to my family and friends

who have all had an impact on my life.

ACKNOWLEDGEMENTS

First, I would like to thank Dr. Yucheng Liu, who has directed me throughout my graduate program and thesis work, without him this thesis would not have been possible. Special thanks go to Dr. Michael Mazzola and John E. Ball for being a part of my committee and aiding me in both the work that led to this thesis and the writing of it. Finally, I would like to thank the Faculty and support staff at the Center for Advanced Vehicular Systems who provided a tremendous amount of aid in completing this project.

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NOMENCLATURE

Nomenclature		Units
t	current time	seconds
Δt	time step $(t_2 - t_1)$	seconds
u(0)	initial position	units of length (feet/meters)
u(t)	current displacement at time t	units of length
u(t+Δt)	next displacement at t+Δt	units of length
v(0)	initial velocity	length per second
v(t)	current velocity at time t	length per second
v(t+Δt)	next velocity at t+Δt	length per second^2
a(0)	initial acceleration	length per second^2
a(t)	current acceleration at time t	length per second^2
a(t+Δt)	next acceleration at t+Δt	units of rotation (degrees/ radians)
θ(0)	initial angular position	units of rotation
θ (t)	current angular displacement at time t	units of rotation
θ(t+Δt)	next angular displacement at t+Δt	units of rotation
ω(0)	initial angular velocity	units of rotation per second
ω (t)	current angular velocity at time t	units of rotation per second
ω(t+Δt)	next angular velocity at t+Δt	units of rotation per second
α(0)	initial angular acceleration	units of rotation per second^2
α (t)	current angular acceleration at time t	units of rotation per second^2
α (t+Δt)	next angular acceleration at t+Δt	units of rotation per second^2
w_t	width of the tractor	units of length
l_t	length of the tractor	units of length
L	length of the hitch	units of length
w_d	width of the dolly	units of length
l_d	length of the dolly	units of length

CHAPTER I

INTRODUCTION

1.1 Objective

The objective of this research is to develop a dynamic model for a cargo tractor-dolly system for collision avoidance. For the experiments this thesis is based on the tractor is a rear wheel drive and front wheel steering, and the dollies are the trailers pulled by the tractor with free caster wheels on the front axle and fixed wheels on the rear axle. The vehicle system that the model represents can be commonly found at airports transporting luggage, crews, or other forms of cargo. At an airport the cargo tractor-dolly system runs the risk of colliding with various obstructions such as ground vehicles and unfortunately, aircraft. A collision between a cargo tractors and an aircraft is a dangerous accident that can happen at any airport, and can cause great financial expense and even fatal injuries. In order to reduce the frequency and severity of cargo tractor- aircraft collisions an avoidance system has to be developed to predict the tractor and its' dollies positions in a reference frame that accounts for all obstructions in the nearby area.

The proposed collision avoidance system uses an array of sensors and computational equipment to provide real time information on the tractor's movement and location. However useful this data is, it does not solve the collision problem as the tractors often have one to four dollies attached to them. The lack of natural predictability of the dollies can lead to a collision between the dollies and obstructions on the airfield as well. The model presented in this thesis provides a solution to the dollies positioning by generating a polygonal shape from the information provided by the sensor array. The hypothesis, referred to as the time delay hypothesis, is that although the dollies do not follow an exact path behind the tractor, it can be assumed that if given enough of a safety threshold a polygon representing the vehicle system will account for any error in the prediction. One focus of this thesis is to detail the polygons generation and how it functions in real time.

1.2 Framework

This section contains a brief description of the model and the concepts used. The development of the model began with a state space model to evaluate position based on Newton's second law. Newton's second law states that the force acting on a body is proportional to the product of the mass and the acceleration in the direction of the force. The law which is defined in Equation 1.1 as Force is equal to mass multiplied by acceleration which was instrumental in our conceptualization of the acceleration and movement of the multiple vehicles that make the model.

$$F = ma \tag{1.1}$$

The basic kinetic and kinematic equations were used in predicting the path that the tractor would follow. Equations 1.2, 1.3, and 1.4, which are the kinematic equations of motion, were used in conceptualizing process to create the state space model that will be further expanded upon in chapter three. In the kinematic equations it should be noted that d is in units of length v is velocity in length per unit of time, a is acceleration in length per unit of time squared, and t is in units of time.

$$d = v_i * t + \frac{1}{2} * a * t^2 \tag{1.2}$$

$$v_f = v_i + a * t \tag{1.3}$$

$$v_f^2 = v_i^2 + 2 * a * d \tag{1.4}$$

All of these methods were used to predict the position and path of the tractor. Once the tractor is evaluated and a polygon representation is created through a series of trigonometric equations. The dollies are hypothesized to follow a similar path to the tractor. Therefore, the predicted path of the dollies is determined by applying a time delay based upon the tractors position.

For validation purposes a drone provided by Mississippi State University's UAV (Unmanned Aerial Vehicle) team collected aerial photos of the vehicle system in motion. The drone's photos when paired with an Inertial Measurement Unit's (IMU) data provided a set of comparable empirical data that allowed for further verification and validation of the model and time delay hypothesis. Once the model was applied to the actual system further validation was conducted through field testing.

All of the remaining sections are as follows: Chapter 2 contains a concise review of the previous work referenced in vehicle dynamics, collision avoidance, and predictive pathing. Chapter 3 provides the fully developed model starting at the fundamental equations, then the dynamic model, and finally the predictive pathing of the dollies for accident avoidance. Chapter 4 provides a thorough explanation on the proving of the validity of the model's various apects.

Chapter 5 details the intended applications as well as the potential applications of the model. Chapter 6 provides a summary of the paper and how it can be improved in future work.

CHAPTER II

LITERATURE REVIEW

In order to form a substantial background for the model in this thesis, a thorough literature review is provided for the following areas: dynamic modeling vehicle systems and predictive modeling for collision avoidance.

2.1 Dynamic Modeling Vehicles

In 2011, Makaras et al. developed a single vehicle model intended for autonomous driving in urban areas. The model is constructed as a dynamic vehicle-environment-driver model, see Figure 1, which can be compared to the model discussed in this thesis [1].

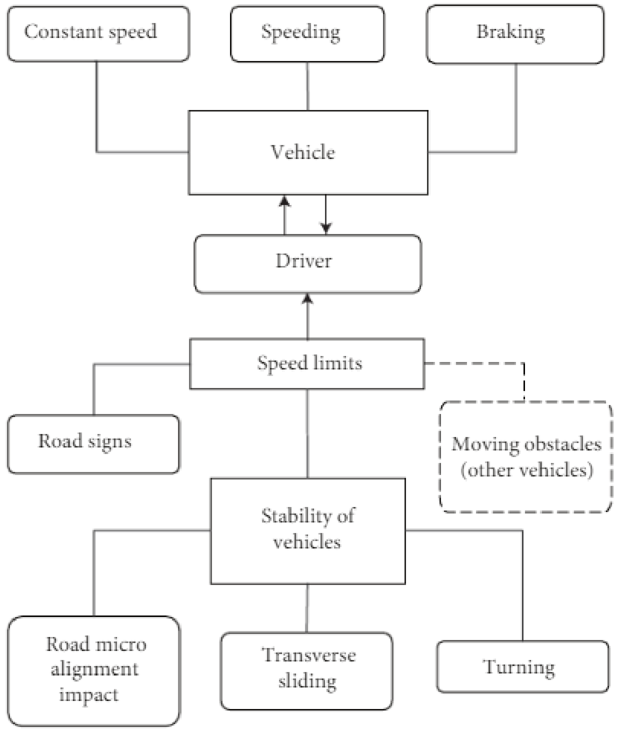


Figure 2.1 The principle framework for the vehicle-environment-driver model [1].

Liu over several different works [2,3] developed a system of equations of motion with 6-degrees-of-freedom (DOF) for a vehicle model. The equations he developed can be used for rigid body analysis such as vibration analysis, frequency domain analysis, and time domain analysis. Next, he developed a 12-DOF vehicle model which can be used in most vehicle model cases [2]. In the second article reviewed. Liu focused on suspension systems in rigid body analysis through “architecture level abstractions for suspension systems” for vehicle models [3]. Both of these articles provided a ground work for developing a vehicle model

Sustersic, et al. in 2010 [4], presented a model of vehicle-trailer system dynamics. The system involved using rigid bodies interconnected with rotational, translational, and spherical kinematic constraints, springs, and dampers all of which influence the sytem motio. The rigid body model used a bicycle type system where each axle is represented by a singular box which can be seen in Figure 2.2. Despite the usefulness of this simplistic model involving a trailer, it did not cover the dynamics of multiple trailers.

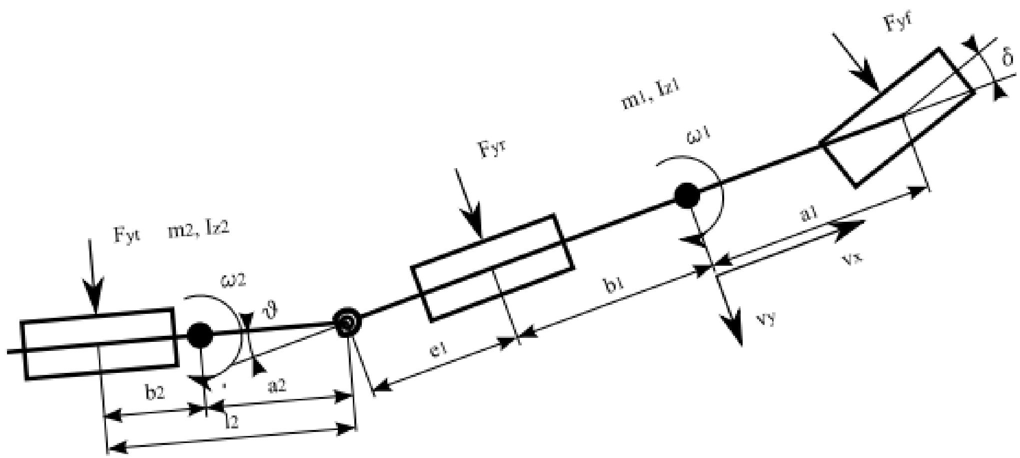


Figure 2.2 Model of a vehicle using rigid bodies with a single trailer.

The units shown are this figure are described as δ-the steering angle; F-Forces on the turn; the dots are hitch points between the towing vehicle and trailers; a, b, e, and l are measurements of length between different parts of the vehicle; ω is the rotation at the hitch; and v is the velocity forces on the turn [4].

Zobel [5] modeled a truck with a trailer with the eventual intention of full automation. He began with a simplistic bicycle model, which is shown in Figure 2.3, where there are only two position parameters, the position of the steering axle and the position of the fixed axle. The model assumes that a predictive curve can be created for both vehicles, but acknowledges the difficulty in predicting the vehicle from one maneuver to another.

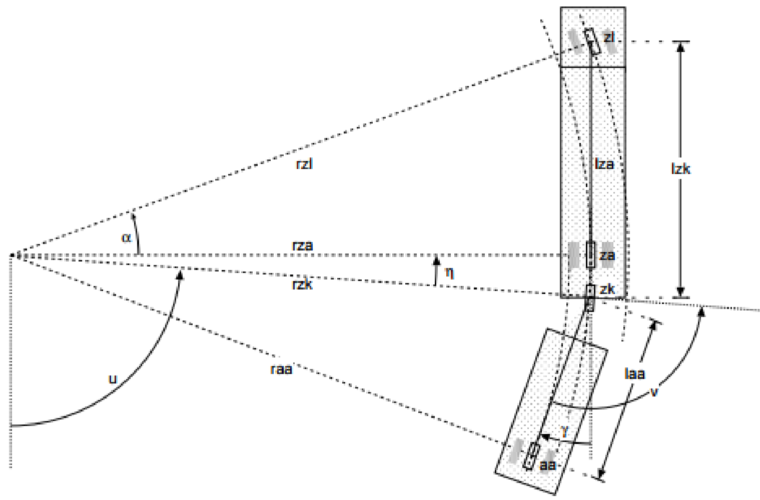


Figure 2.3 Geometric model of a truck with a single trailer.

The variables are defined as: zl- the center of the front axle; lza the length between the front and rear axle; za the rear axle; zk the hitch on the towing vehicle; lzk the length between the front axle and hitch of the towing vehicle; laa the length between the hitch of the towing vehicle and the rear axle of the trailer; ϒ the angle of the trailer with reference to the towing vehicle; α the steering angle of the towing vehicle; rzl, rza, and raa represent radii solved for in the turn of the vehicle system; u is the traction point; and v is the direction of the trailer with reference to the origin [5].

2.2 Predictive Modeling for Collision Avoidance

Pepy et. al [6] addressed the problem of path planning using a dynamic vehicle model for autonomous driving. A kinematic model was presented in simple 2D space a realistic path planner based on a dynamic vehicle model was proposed. To begin, Pepy and his team presented a simplistic differential model that assumed that a correction factor was not needed, but the limits of this simplistic system would lead to collisions. A more dynamic model was presented that included tire to road interaction, and increased the degrees of freedom significantly. From Pepy's work it was found that conditions for the tractor and what factors can be ignored were comparable to the work presented in this thesis. Despite the potential of this model it lacked validation, and in some ways, went beyond the scope of this thesis.

Caveney investigated the fusion of digital maps and dynamical models to accurately predict the future path of a vehicle [7]. The system functioned through the sharing of information between vehicles through wireless channels. The method behind the general function of the system was a dynamic vehicle model that accounted for mass, wheel base, steering ratio, as well as IMU data to work in concert with digital maps and the vehicle communication system.

The limitations of the system were mostly found to be with the Global Positioning System (GPS) and the IMU's measurements. From this article it can be ascertained that the IMU, while useful, needs experimentation to determine how best to generate a dynamic model. The article also suggests that using GPS could be a viable way in comparing a digitally created path to a physical one.

Fernandez [8] developed a new vehicle dynamics model with 10 degrees of freedom for real-time applications, primarily intended for driving simulators. This model is intended to calculate the motion of a passenger vehicle when driving in normal conditions, representing real vehicle behavior in public roads. In addition, the model also presents a realistic and predictable behavior in some severe driving conditions such as collision avoidance manoeuvers.

Silva [9] addressed the path following problem of a wheeled mobile robot with rhombic like kinematics operating cluttered environments. Four path following controllers were developed to steer the kinematic model of a rhombic-like vehicle along a desired path. Simulated results presented a comparative performance assessment of the controllers while dealing, or not, with vehicle dynamics. The methods presented in this paper were somewhat applicable to the work in this thesis, but lacked the vehicle dynamics that could be applied to a tractor-dolly system.

Stigers et al. [10] integrated a previously developed dynamic track model to a detailed model so that a vehicle-track dynamic interaction could be realistically simulated. Like the model Pepy's team presented [4], Stigers' vehicle-track dynamic model needs to be tested to demonstrate the coupling effect and to acquire a better understanding on the vehicle and track behavior under different riding conditions.

Na et. al [11] developed an experimental vehicle model, which employed experimental kinematic and compliance data measured between the wheel and chassis. From the compliance data, a vehicle model, which included dynamic effects due to vehicle geometry changes, was developed. The experimental vehicle model was validated using an instrumented experimental vehicle and data such as a step change steering input.

Different from the previous vehicle odels which focused on modeling of a single rigid vehicle body or single vehicle with one trailer, the dynamic model presented allows for the predicted position and path of multiple trailers or dollies in a towed system. The model presented also uses a series of controls and sensors such as the IMU that simplifies the system over many of the previous works. Horsepower, torque, and wheel to pavement interaction, which are prevalent in previous works, were also removed from the model once they were determined to be outside the scope of the problem at hand. The next chapter details the model and its development.

CHAPTER III

DEVELOPING THE MODEL

The framework of the dynamic polygon model requires a large amount of flexibility to account for various conditions and inputs. Similar to Makaras's team [4] a dynamic vehicle-driver-environment system needed to be created and is represented in Figure 3.1. Development of the system began with establishing the basic requirements of the problem a state space model based on Newton's second law, and was developed with the intention of processing the large amount of input data into an observable system. The next portion of the framework is a model that converts angular acceleration into angular position to determine where the dollies are in respect to the tractor. The third and final portion of the framework is the development of a series of equations with the intent of creating a polygon representation of the vehicle system for collision avoidance which is shown in Figure 3.2. The polygon is modeled as larger than the actual vehicle so that it can function as a threshold of safety to account for any error or unpredictable variation that occurs in the system.

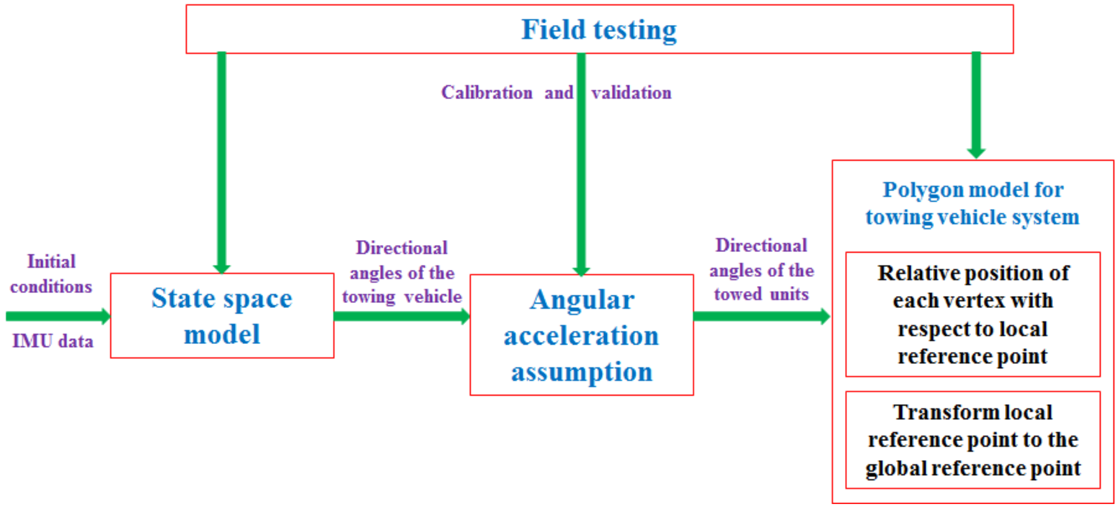


Figure 3.1 Framework of the developed dynamic model.

3.1 State Space Model

As mentioned before the state space model is based on Newton's second law. Three degrees of freedom are assumed with translation on the x-y-z axes where x is horizontal distance traveled from the origin, y is the forward distance traveled from the origin and z represents the turning axis. To properly represent the dynamics of the rigid body shown in Figure 5 a discrete system model was created in the form of a state space matrix.

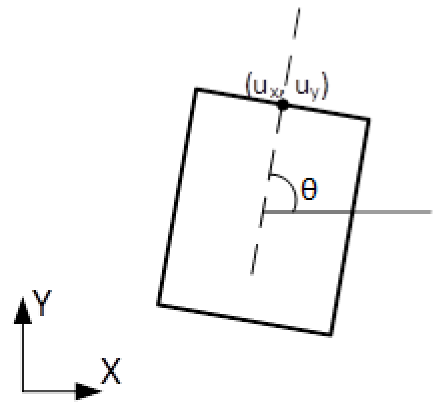


Figure 3.2 Single rigid body model.

Eqn. (3.1) is the state space model created for this system it provides, the position in the x and y as u, angle with respect to starting position θ, velocity in the x and y as v, as well as the angular velocity as ω. Due to the limitations of the sensor equipment, angular acceleration was not included. The primary variable that should be noted is Δt of the system provides the change in time between each polygonal representation. The state space model can be applied to all of the vehicles in the system. The initial conditions for the state space model are provided by an IMU (inertial measurement unit) which can register real time linear and angular motion.

$$\begin{pmatrix} u_x(t+\Delta t) \\ u_y(t+\Delta t) \\ \theta(t+\Delta t) \\ v_x(t+\Delta t) \\ v_y(t+\Delta t) \\ \omega(t+\Delta t) \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta t \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} u_x(t) \\ u_y(t) \\ \theta(t) \\ v_x(t) \\ v_y(t) \\ \omega(t) \end{pmatrix} + \begin{bmatrix} \frac{\Delta t^2}{2} & 0 & 0 \\ 0 & \frac{\Delta t^2}{2} & 0 \\ 0 & 0 & \frac{\Delta t^2}{2} \\ \Delta t & 0 & 0 \\ 0 & \Delta t & 0 \\ 0 & 0 & \Delta t \end{bmatrix} \begin{Bmatrix} a_x(t) \\ a_y(t) \\ \alpha(t) \end{Bmatrix} \quad (3.1)$$

$$\frac{v_x(t)}{v_y(t)} = \frac{a_x(t)}{a_y(t)} = \tan(\theta(t)) \quad (3.2)$$

Eqn. (3.1) and Eqn. (3.2) will rely on the IMU system installed on the tractor for the real time linear and angular acceleration data. With the initial conditions and IMU data Eqn. (3.1) and (3.2) can determine position, directional angle, and linear and angular velocity of the tractor for any Δt.

3.2 Angular Acceleration Transferring Model

Although the IMU coupled with the state space model provides the current position and the predicted position of the tractor, it does not allow for the prediction of the dollies locations. The dollies can potentially collide with obstructions in the vehicles area of operation; therefore it was necessary to create a system for predicting the directional angle for the dollies.

To solve the issue of predicting dolly angles, an acceleration transferring mode was proposed based on the following observations: (1) when moving along a straight path all the dollies move with the same velocity and acceleration as the tractor; (2) after finishing a turn the tractor and all dollies move together with the same velocity and acceleration; (3) during a turn the tractor and dollies rotate the same angular distance. With these observations an assumption was made that the dollies acquire the same angular acceleration of the tractor after a time delay. Fig. 3 displays the assumption through a curve where each “unit” is a sequential dolly in the system. With this angular acceleration transferring model the instantaneous angular acceleration for each vehicle can be determined.

It should be noted that by establishing the hypothesis that each dolly follows the same sequence of directional angles as the tractor “off-tracking” is neglected. The off-tracking effect is that a towed vehicle always follows a tighter path on a turn than the leading towing vehicle does. The reasoning behind ignoring is that it requires instantaneous angular rotation on each independent vehicle which is impossible to determine without sensor units, such as the IMU, being installed on each one. It is also negligible due to the low operating speeds of the tractor dolly system and similar sizes in both length and width between the tractor and its subsequent dollies, as off-tracking is most noticeable on large tractor-trailers where the trailer is significantly longer than the tractor. Despite the off-tracking effect being ignored it is expected that the error in predictive pathing of the dollies should be controllable. Based on these assumptions and observations off-tracking was ignored, but the error is accounted for in the polygon model in the next section. Also, all assumptions were tested and validated in Chapter 4.

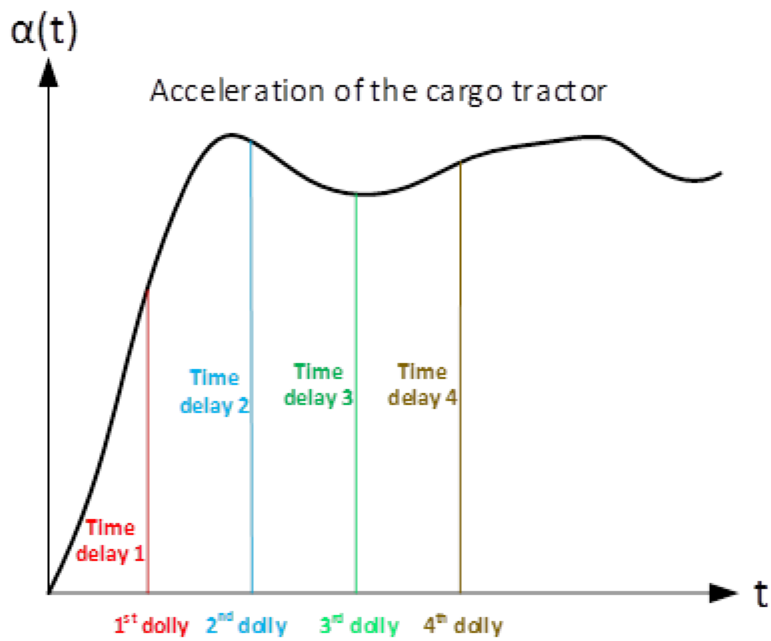


Figure 3.3 Angular acceleration curve for the tractor and dollies

Currently the angular acceleration transferring model allows for much simpler predictive pathing than would otherwise be used. Due to the angular velocity and position being dependent on angular acceleration transferring the tractors known angular velocity to the dollies allows for a representation of the path its taking to be created.

3.3 Polygon Model

A polygon model is presented to provide a visible predicted shape and approximated direction of the vehicle system at any time. A beacon system involving modified traffic cones with tape that is recognized by the sensor system is used to provide reference points that constantly update the polygon model of its location with respect to the objects in its environment. The beacon system is an important input parameter on this model because without it the system would not know when a collision is imminent.

Several assumptions were made before developing the polygon model: (1) The current (time=0) position of the front tractor is considered to always be at O or (0,0), but for predicting the path the location can be easily modified by changing O's current coordinates. (2) The tractor and its dollies are all considered to be rigid rectangles with four vertices, which will be connected by line segments. (3) Each dolly will be of equal size and follow similar pathing. Figure 7 provides a basic representation of the tractor with four vertices represented at the corners by 1, 2, 3, and 4. Also note the location of O and TRH (Tractor Rear Hitch), and how the turning angle of the tractor is represented with θ_0 which is the steering angle which is simplified into the orientation of the tractor with respect to its' previous position.

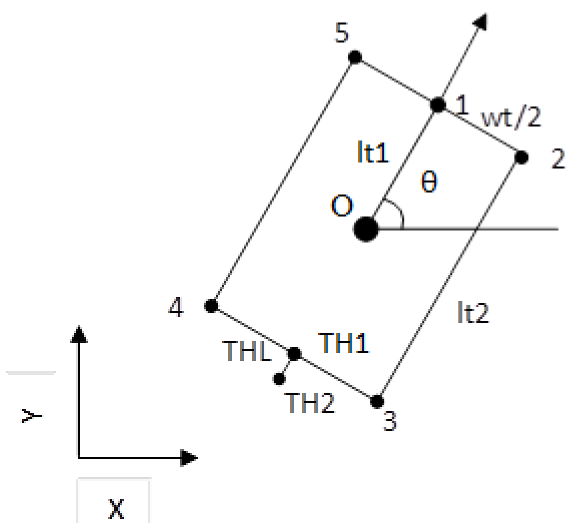


Figure 3.4 Sketch of the tractor model.

The numbers are the vertices (corners) of the simplified tractor, wt is the width of the tractor, lt1 is the length from the front of the tractor to the origin point O, lt2 is the total length of the tractor, THL is the hitch length and TH1-2 are the fixed and free ends of the hitch respectively.

Each part of Equation (3.3) represents a point on Figure 7 where (x_1, y_1), (x_2, y_2), (x_3, y_3), and (x_4, y_4) represent the locations of points 1, 2, 3, and 4, respectively, in reference to O. The point TRH represents the hitch located at the back of the tractor and provides the connecting and pivot point of the dolly following after it. The tractors dimensions are represented by w_t and l_t which are the width and length of the tractor. The points combined draw the lines that create the simple rigid body representation of the tractor, respectively.

$$x_1 = O + l_{t1}\sin(\theta_t), y_1 = O + l_{t1}\cos(\theta_t)$$

$$x_2 = x_1 + \left(\frac{w_t}{2}\right)\cos(\theta_t), y_2 = y_1 + \frac{w_t}{2}\sin(-\theta_t)$$

$$x_3 = x_2 - l_{t2}\sin(\theta_t), y_3 = y_2 - l_{t2}\cos(\theta_t)$$

$$THX_1 = x_3 - \frac{w_t}{2}\cos(-\theta_t), THY_1 = y_3 - \frac{w_t}{2}\sin(-\theta_t)$$

$$THX_2 = THX_1 + THL * \sin(-\theta_t), THY_2 = THY_1 - THL * \cos(-\theta_t)$$

$$x_4 = THX_1 - \frac{w_t}{2}\cos(\theta_t), y_4 = THY_1 - \frac{w_t}{2}\sin(-\theta_t)$$

$$x_5 = x_4 + l_{t2}\sin(\theta_t), y_5 = y_4 + l_{t2}\cos(\theta_t)$$

(3.3)

Once the tractor is represented the first dolly is added by connecting it to the TRH point. In Figure 8 the Dolly 1 is added where θ_0 represents the turning angle applied to the tractor and θ_1 representes the turning angle for Dolly 1. It is important to note the green and red dots each representing a side of the hitch, the red dot represents where the hitch is fixed to Dolly 1 and the green dot represents TRH which Dolly 1 rotates about. The angle for each vehicle is the primary variable for determining the location of the dollies with respect to the tractor.

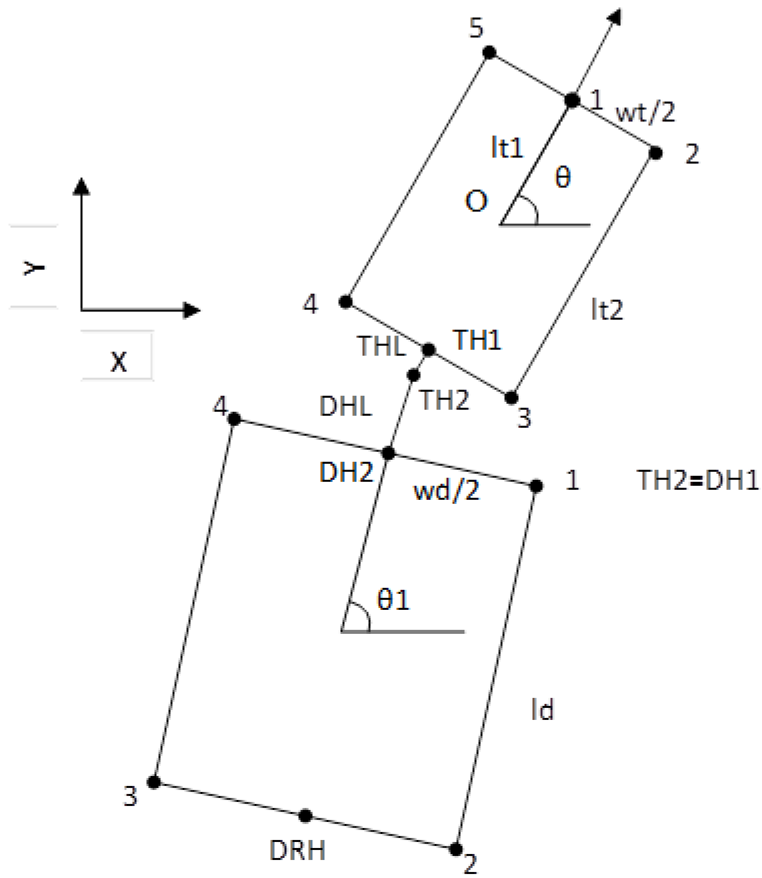


Figure 3.5 Sketch of a cargo tractor with one dolly model.

Points 1, 2, 3, and 4 on the dolly act similarly to the tractors points 2-5. The width and length of the dolly are represented by wd and ld. The dolly's front hitch is denoted by DH1 and DH2 with a length of DHL and the rear hitch is DRH.

Dolly 1

$$DHX_1 = THX_2, DHY_1 = THY_2$$

$$DHX_2 = DHX_1 - DHL * \sin(\theta_1), DHY_2 = DHY_1 - DHL * cos(\theta_1)$$

$$x_1 = DHX_2 + \frac{w_d}{2} * \cos(\theta_1), y_1 = DHY_2 - \frac{w_d}{2} * \sin(\theta_1)$$

$$x_2 = x_1 - l_d * \sin(\theta_1), y_2 = y_1 - l_d * \cos(\theta_1)$$

$$DHXR_1 = x_2 - \frac{w_d}{2}\cos(\theta_1), DHYR_1 = y_2 + \frac{w_d}{2}\sin(\theta_1)$$

$$x_3 = DHXR_1 - \frac{w_d}{2}\cos(\theta_1), y_3 = DHYR_1 + \frac{w_d}{2}\sin(\theta_1)$$

$$x_4 = x_3 + l_d \sin(\theta_1), y_4 = x_3 + l_d\cos(\theta_1)$$

(3.4)

All of the dollies can be surmised in the general system of equations provided below. These equations present the possibility for an infinite number of dollies where the θ is the primary variable that changes throughout the system.

Generalized Dolly Equations

$$DHX_i = DHXR_i - DHL * \sin(\theta_i)\,, DHY_i = DHY_i - DHL * cos(\theta_i)$$

$$x_1 = DHX_i + \frac{w_d}{2} * \cos(\theta_i)\,, y_1 = DHY_i - \frac{w_d}{2} * \sin(\theta_i)$$

$$x_2 = x_1 - l_d * \sin(\theta_i)\,, y_2 = y_1 - l_d * \cos(\theta_i)$$

$$DHXR_i = x_2 - \tfrac{w_d}{2}\cos(\theta_i)\,, DHYR_i = y_2 + \tfrac{w_d}{2}\sin(\theta_i)$$

$$x_3 = DHXR_i - \frac{w_d}{2}\cos(\theta_i)\,, y_3 = DHYR_i + \frac{w_d}{2}\sin(\theta_i)$$

$$x_4 = x_3 + l_d \sin(\theta_i)\,, y_4 = x_3 + l_d\cos(\theta_i)$$

(3.5)

When Eqns. (3.5) are applied they develop a polygon model that provides an envelope which represents the real system. The number of dollies following the tractor is arbitrary using Eqns. (3.5), but Figure 3.6. below provides a representation of what the total system used in testing looked like. The key steps in the methodology presented are: (1) starting from O all of the lines and vertices represent a rigid body system, which requires the input of an angle for each individual part. (2) Each angle is calculated for by the state space equation which uses data from the sensor array.

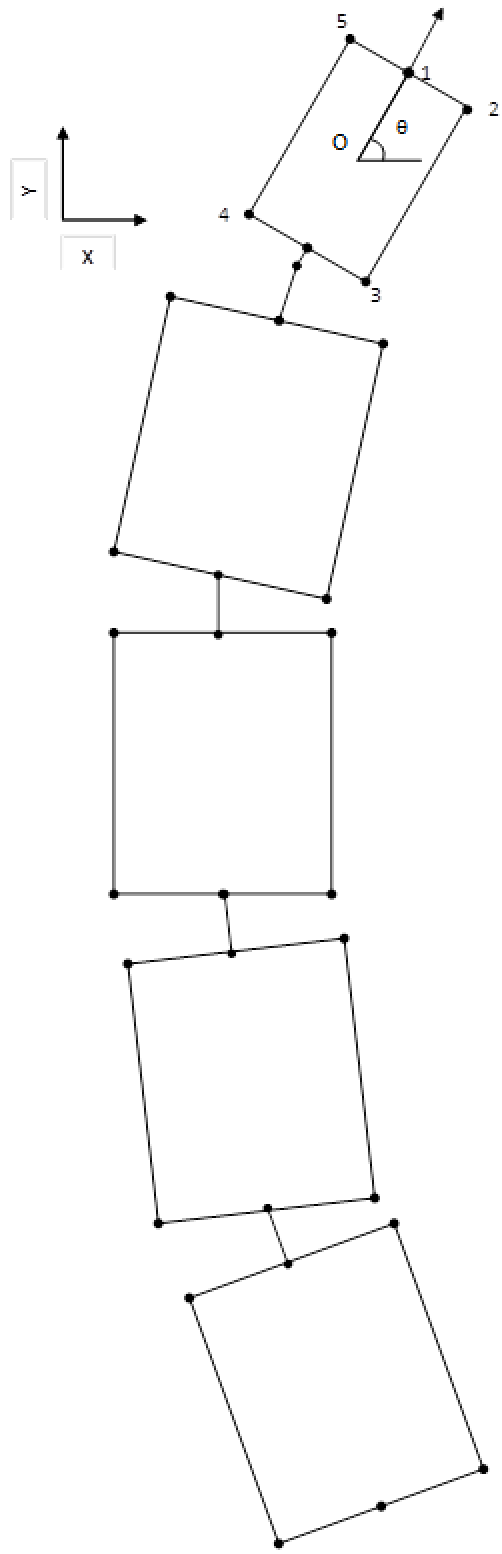


Figure 3.6 Total polygon representation used in testing with four dollies.

3.4 Summary of Dynamic Model

The model presented from the aforementioned framework is displayed in Figure 10. The first stage of the model establishes the initial conditions and starting point of the system using the IMU (inertial measurement unit). The second stage process the data and performs the state space equations required to produce stage 3. Stage 3 is the visual out of the tractor where its position is determined. The fourth stage uses the position of the tractor and estimates a time delay for stage 5. Stage 5 re-evaluates the state space model and applies it to the conditions for the first dolly. Stage 6 produces the approximated position of the first dolly. Stages 7-9 follow a similar path to stages 4-6 except that the Δt would be longer than the previous dolly. Stages 10-12 represent the potential for more dollies being applied, but with the condition of Δt increasing for each consecutive vehicle.

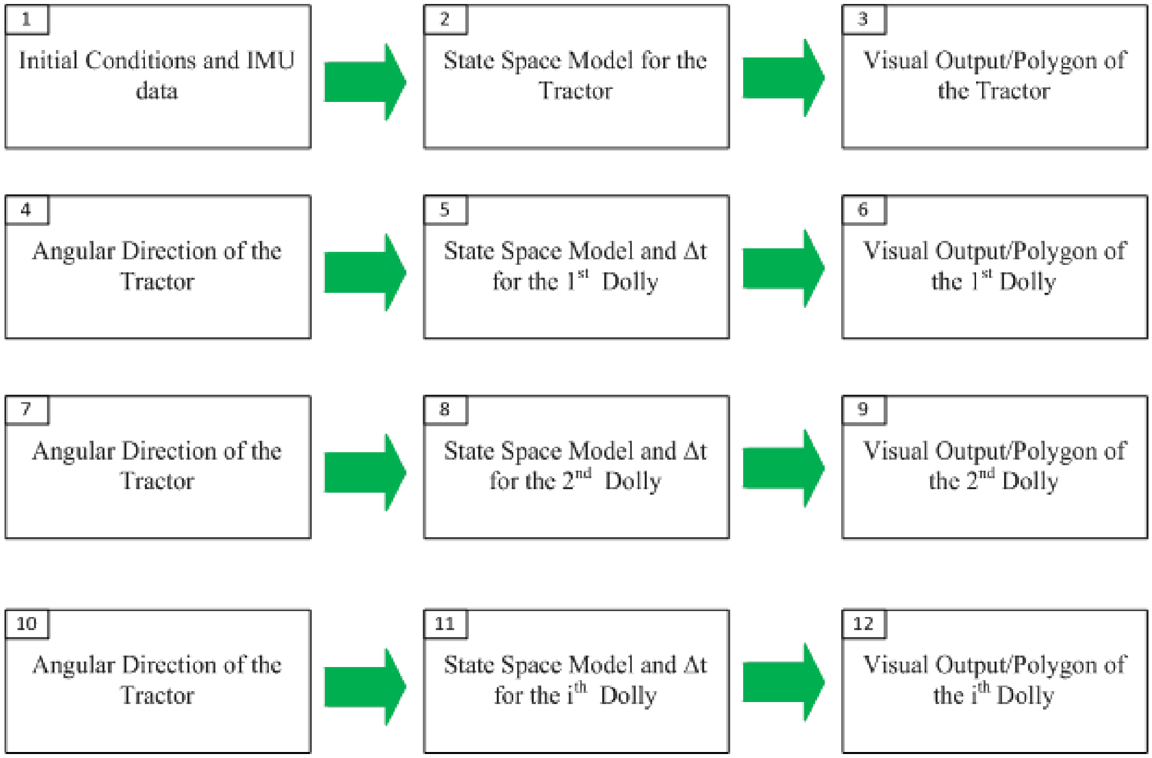


Figure 3.7 The dynamic model that creates the polygon display of the Tractor as well as the consecutive Dollies up to the i^{th} Dolly.

CHAPTER IV

VALIDATION

Validation was performed in several steps that included a series of field tests to determine the effectiveness of the modeling framework in representing the instantaneous shape of the tractor-dolly system. Ten test runs were conducted in which the driver of the tractor performed several different maneuvers at speeds of 2mph and 5mph. The testing area was the parking lot of the Center for Advanced Vehicular Systems (CAVS) which provided a flat testing area similar to the airfield that the tractor-dolly system would normally be operating on. The IMU recorded output accelerations of the driving system at increments of 0.001seconds. To provide a comparable frame to the IMU data a drone, which can be viewed in Figure 4.1 was equipped with a high resolution camera that and flown to a height of 40 meters which allowed a complete view of the maneuvers. The camera was set to capture an image at 1 frame per second and was timed to begin recording at the same time as the IMU was. A set of photographs and comparable IMU data was captured for the 10 test runs and were used for further analyses. Each run was approximately two minutes long providing close to 120 images for each test run.

Figure 4.1 Drone used in testing for taking aerial photographs of the tractor-dolly system

4.1 Validation of the Polygon Model

When validating the dynamic model, its three primary components were separated for validation. The first to be validated was the polygon model which was tested for its accuracy in depicting a reliable shape to represent the tractor-dolly system if the correct directional angles are provided. Figure 4.2 provides an aerial photograph of the testing area at CAVS and displays the starting point of the tractor-dolly system. From that point the drone and IMU were synced providing comparable data as the vehicle system performed various maneuvers.

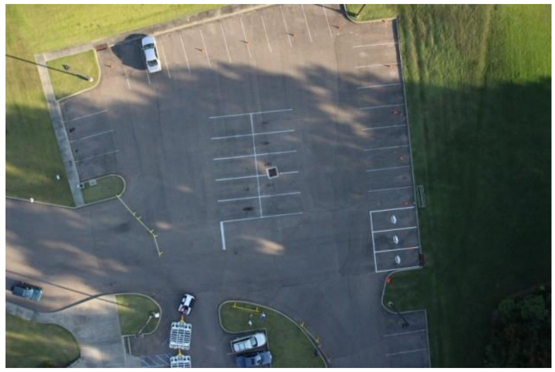


Figure 4.2 Tractor-Dolly system at time 0s with the parking lot that was used for a testing area.

Forty-three images from time 15s to 58s were evaluated on the first run. Validation of the model was performed by the angle of the tractor with respect to a determined x-y plane and the measuring all of the dolly's angles with respect to the tractor. Once these measurements were completed the directional angles were input into Eqns. (3.3-3.5) and compared to the aerial images. Figure 4.3 provides the vehicle system at a time of 15 seconds into the first test run and its comparable representation in Excel.

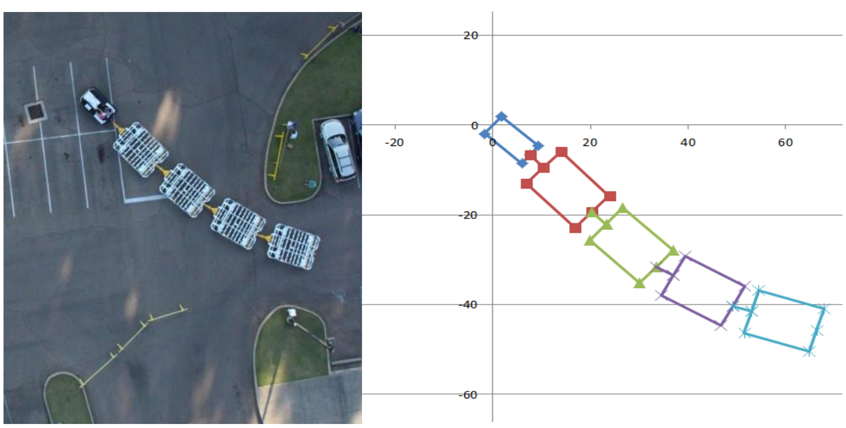


Figure 4.3 At time 15 compared to Excel representation which uses Eqns (3.3-3.5) The units of the Excel image are in feet.

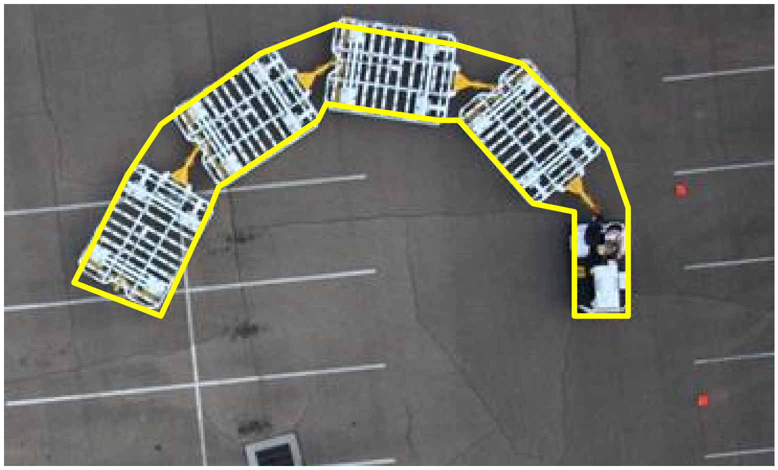


Figure 4.4 Polygon model overlaid onto a turning maneuver.

As shown in Fig. 4.4, it was found that on receiving the angles directly measured from the towing vehicle and the towed units, the developed polygon model can exactly outline the shape of the system, whose accuracy was therefore verified.

4.2 Validation of the State Space Model

The second primary part of the dynamic model to be validated was the state space model to test its' ability to produce the angle of the towing vehicle based on the IMU data. The IMU data used in this section was also from the Section 4.1. The IMU records six types of data that can be used to determine a usable angle: linear acceleration along the x, y, and z axis and angular velocity along the x, y, and z direction. Data recorded in the z axis was neglected due to the test are being flat. With only the x and y being considered the state space model was simplified into Eqn. (4.1).

$$(t+\Delta t)=(t)+\Delta t\times\omega t(t) \tag{4.1}$$

Assuming that at time 0 seconds (starting position) that the tractor angle $\theta_t(t)$ is 0, then Δt and ω(t) could be directly found from the IMU data, the current angles at any given point can be solved through Eqn. 4.1. The calculated angles were compared to the angles measured from the aerial images. Through this comparison it was found that the calculated and measured angles were reasonably close to each other thus verifying the state space model. Figure 4.6 is one the comparison between the measurements and the IMU on the first test run.

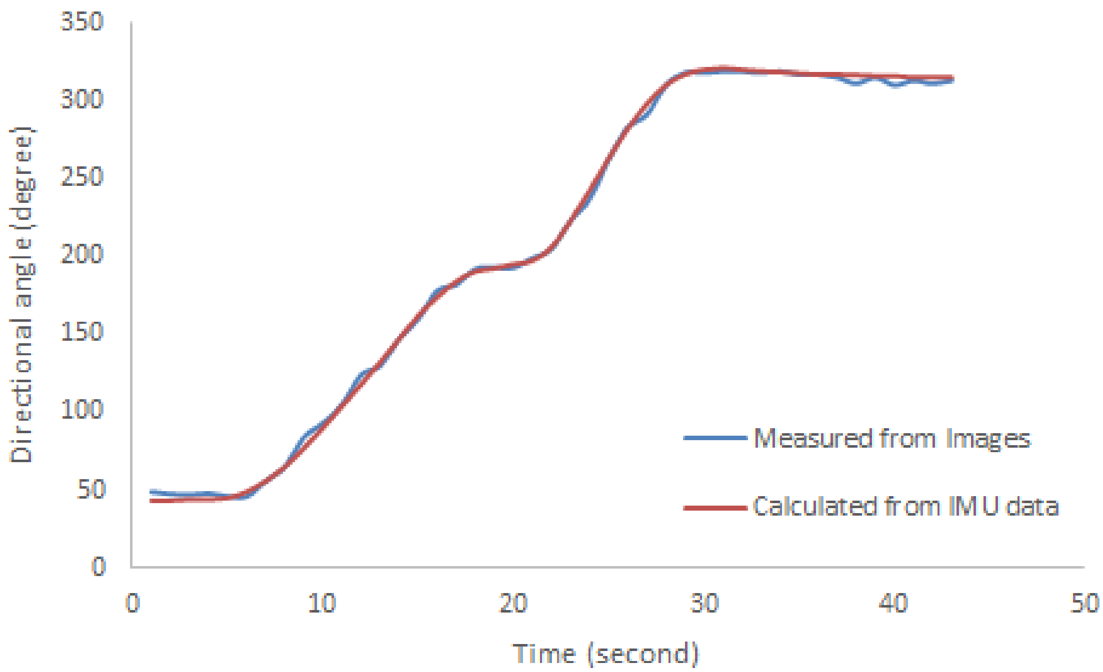


Figure 4.5 Graph comparing the measured angle of the tractor and compared to the IMU's recorded movements for validation of measuring method.

4.3 Validation of the Dolly Angle Model

The dolly angle angular acceleration transferring hypothesis that each towed unit follows the same sequence of angles as the tractor was the third and final part of the validation process. To start the validation, the measurements from the aerial images were input to form the graph in Figure 4.7, which displays the change in angle throughout a portion of the first and third test run that involved a turn. From Figure 4.7, that the curves of each individual vehicle are similar except for the delay in time between each one as the turn begins at approximately 7s and ends when the lines overlap which represents the vehicle system straightening out. This study was repeated for several of the runs to determine through inspection that the delay of each sequential vehicle for average operating speeds are 2s between the tractor and first dolly; 3s between the first dolly and second dolly; 3s between the 2nd dolly and 3rd dolly; 3s between the 3rd dolly and 4th dolly.

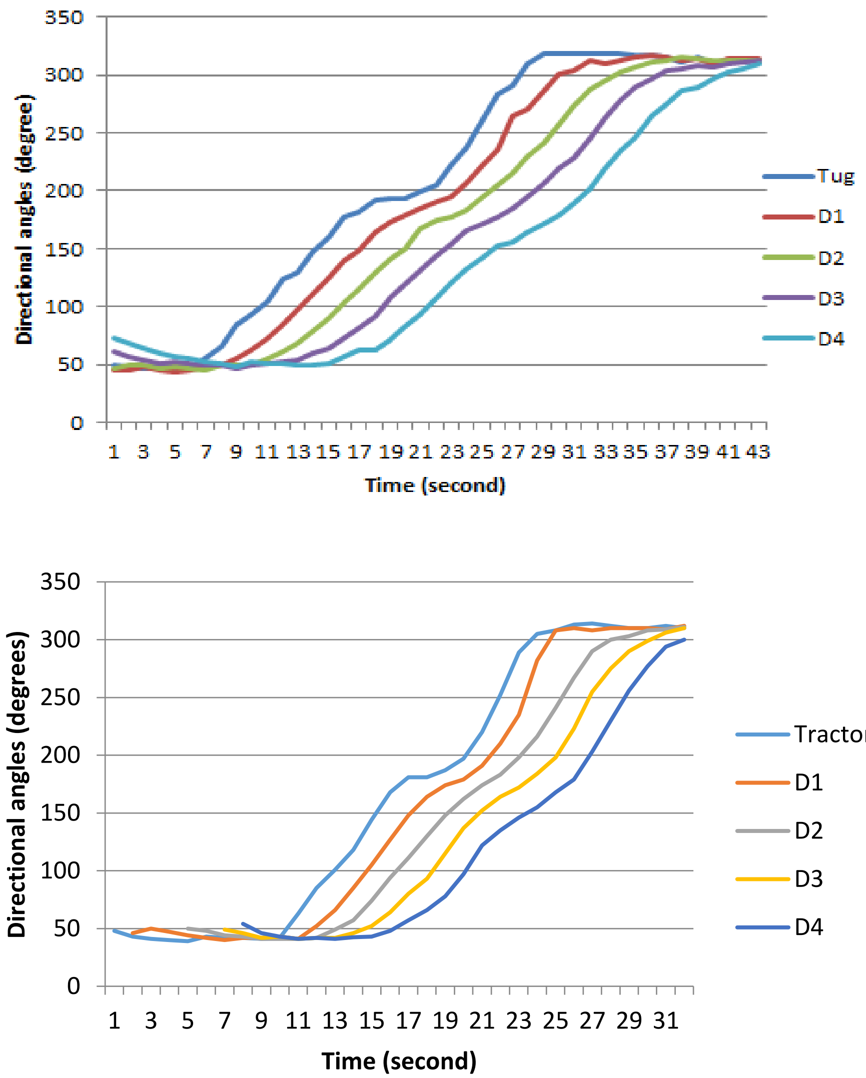
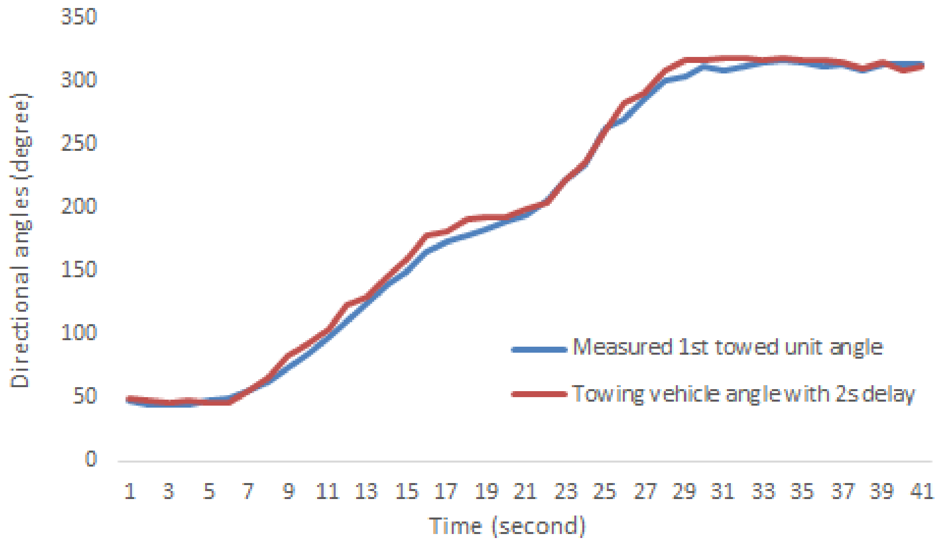


Figure 4.6 Directional angles of the tractor and four dollies for a turning maneuver from the first and 3rd test run.

Notice the error between the first and third dolly this is thought to be either due to maneuvering quickly or faster linear speeds.

To further display how the tractor and dolly paths are similar the curve of each dolly was overlapped with the tractors'. Figures 4.9-4.11 are the comparisons between the tractors change in angle and each individual dollies change in angle for the first and third run. The reason for this comparison should be restated as the IMU is only recording data from the tractor so all following dollies must be accounted for through an estimated prediction such as the time delay model. The estimated time delay is applied to each vehicle to display the overlap. The time delays chosen are from an empirical study used to determine the best curve fit for the dolly and tractor. It should be noted that these angles are strictly found from the individual rotations of each part of the vehicle system and do not include off tracking effects or linear movement as it is assumed that will be known from the IMU. The Root Mean Squared Error (RMSE) was provided for each case note that the smaller the number the better the curve fit.



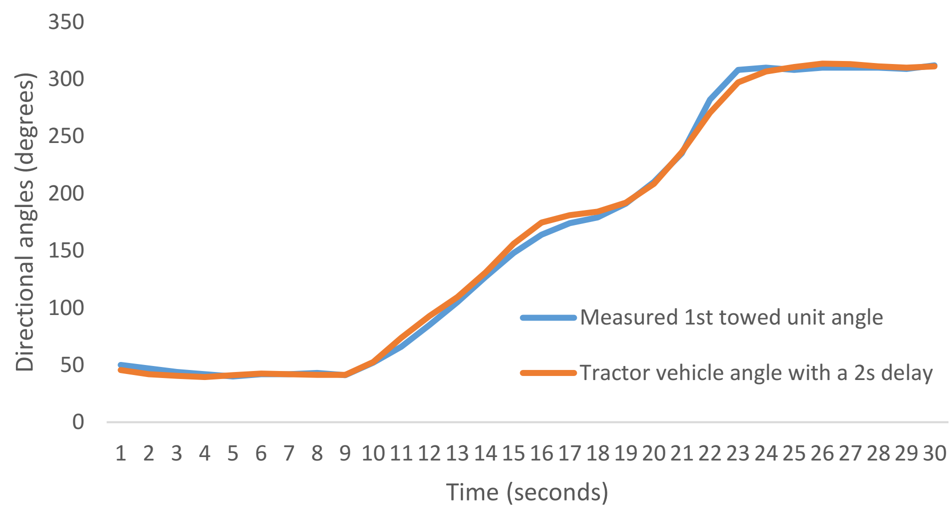


Figure 4.7 Comparison of the angles between the tractor and first dolly for both the first and third test run with a 2 second delay.

The RMSE for the first test run was 6.87 and the third run is 5.28.

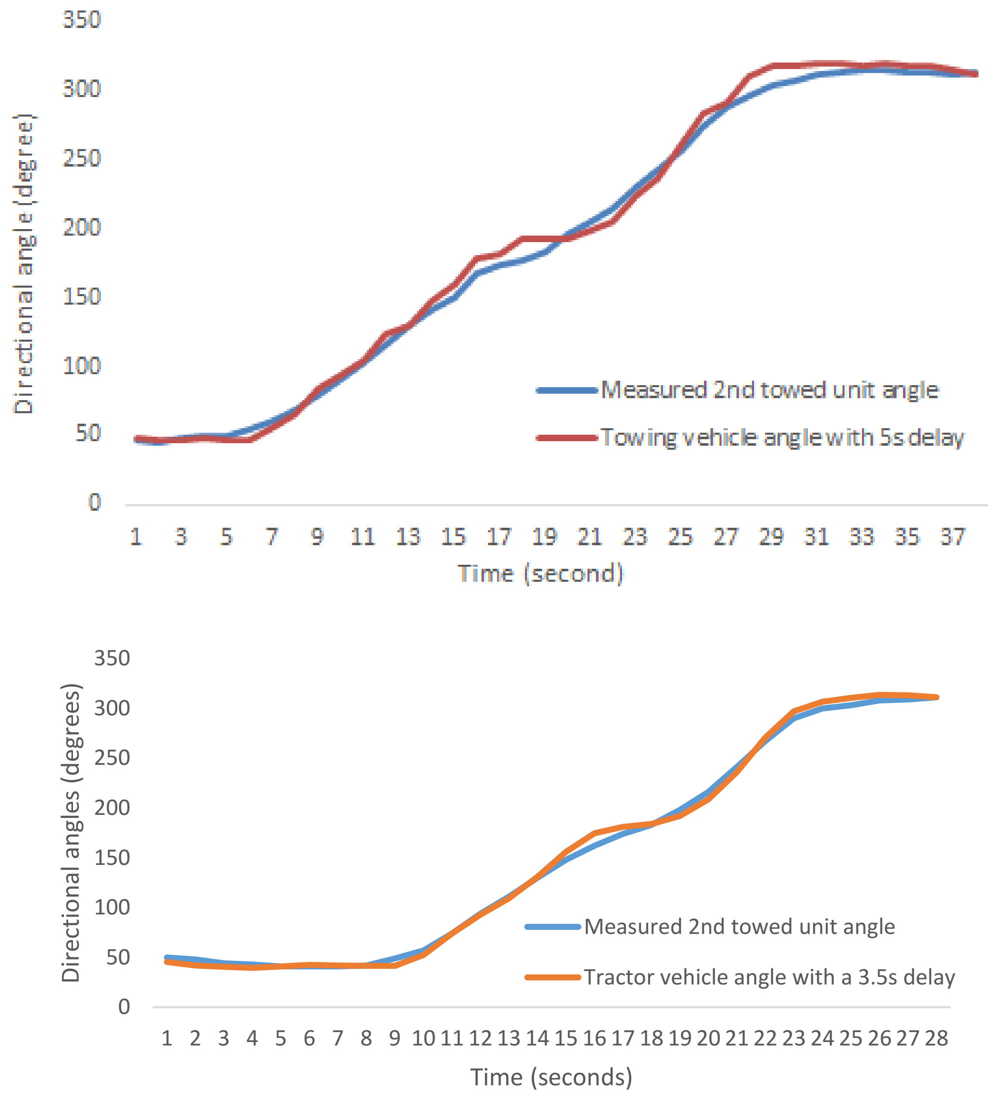


Figure 4.8 Comparison of the angles between the tractor and second dolly for the first and third test runs with a 5 and 3.5 second delay respectively.

The RMSE for the first test run was 6.84 and the third run is 5.3.

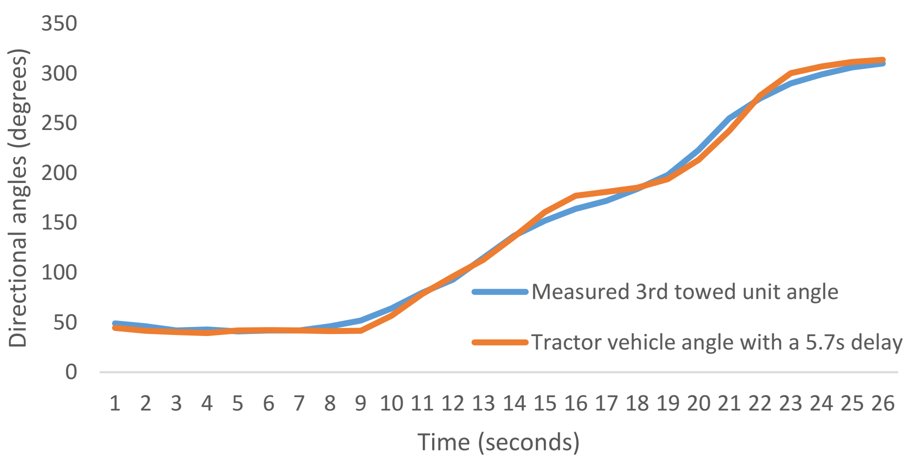
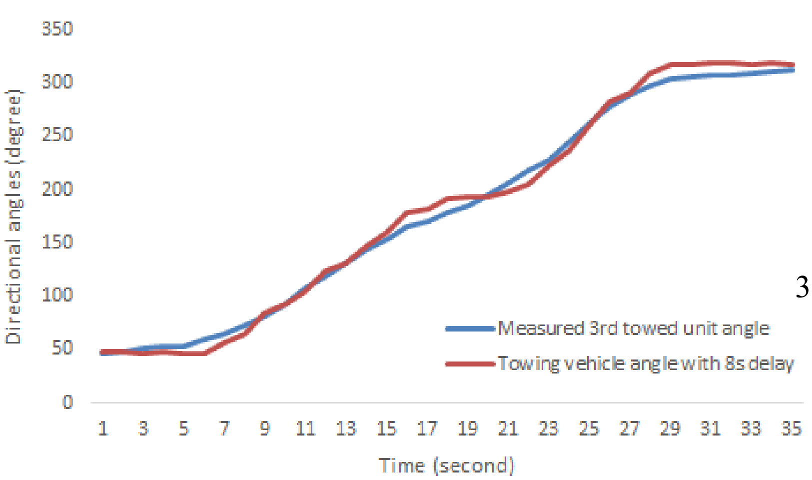


Figure 4.9 Comparison of the angles between the tractor and third dolly during the first and third test run with an 8 and 5.7 second delay respectively.

The RMSE for the first test run 7.57 was and the third run is 6.45.



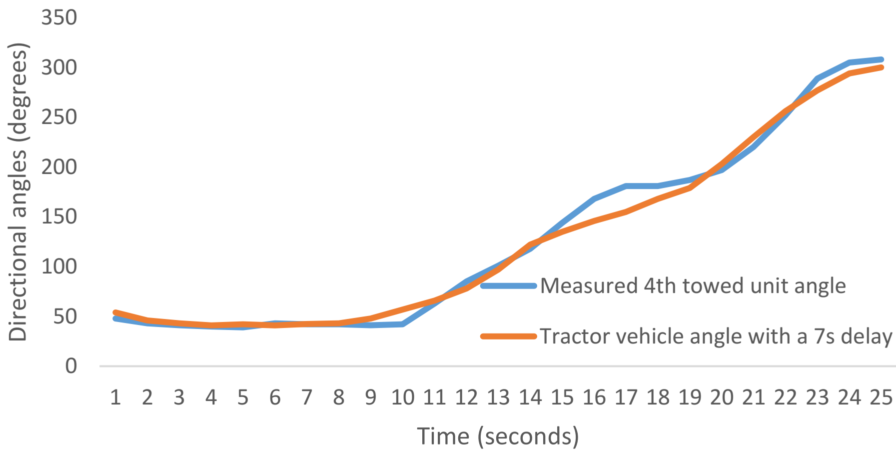
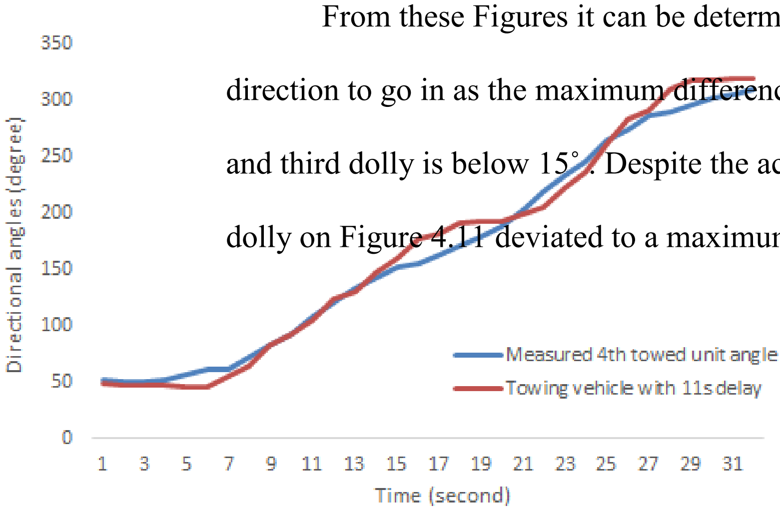


Figure 4.10 Comparison of the angles between the tractor and fourth dolly from test one and three with an 11 and 7 second delay respectively.

The RMSE for the first test run was and 9.72 the third run is 9.76.

From these Figures it can be determined that a time delay model is an appropriate direction to go in as the maximum difference of angle between the tractor or the 1st, 2nd, and third dolly is below 15˚. Despite the accuracy of the first three dollies, the fourth dolly on Figure 4.11 deviated to a maximum deviation of 22˚. After noticing this



considerable deviation a review of the previous figure showed a trend of increasing deviation between each sequential dolly that did not build up to a concerning degree until the 4th dolly. A possible explanation behind this deviation is the neglecting of the "off-tracking error" discussed in section 3.2 which compounded through each vehicle. Another possible explanation can be determined from Figure 4.10 where there are points at which noticeable deviation occurred. This suggests that when the tractor is turning with a high angular velocity, more time is needed to for the dolly to align the tractor's angle.

Another series of test were conducted to determine the actual cause of the deviation in the tractor and fourth dolly's path for comparison. In this comparison the each dolly was compared to the previous one instead of a comparison with the tractor. The first comparison in Figure 4.12, displays the first dolly compared to the second dolly with a 3s delay. In Figure 4.13 a comparison between the second and third dolly is shown with a 3s delay. Finally, Figure 4.14 displays the comparison of the 3rd and 4th dollies with a 3s delay applied.

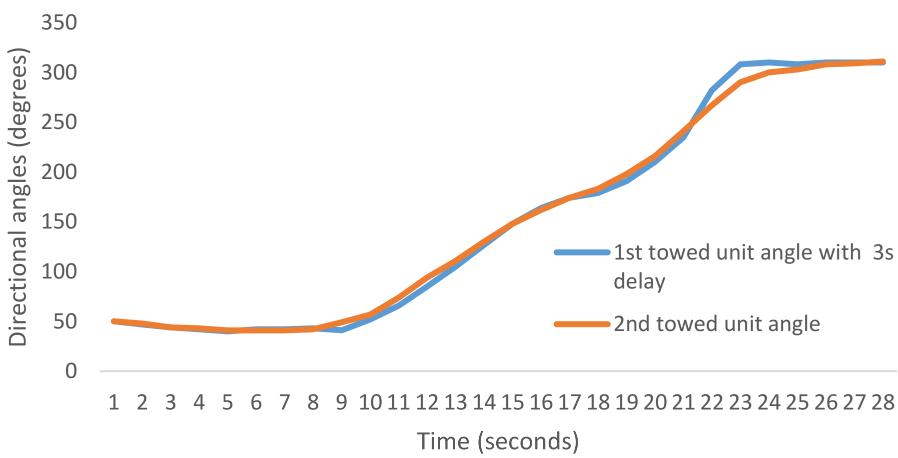
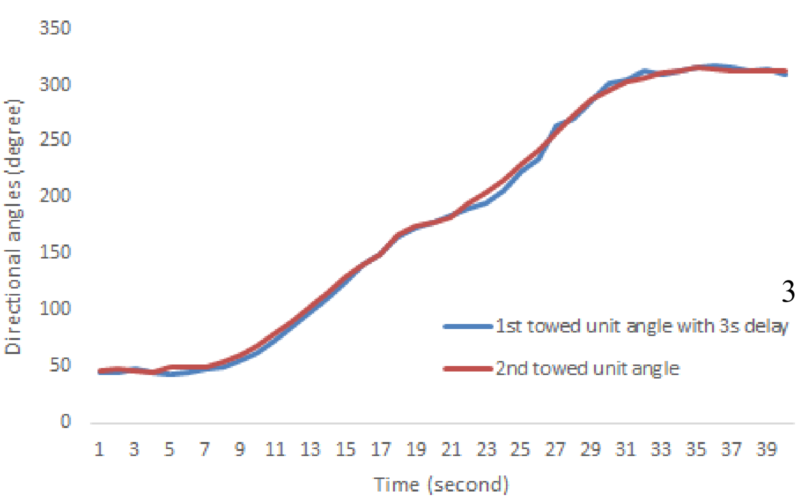


Figure 4.11 Comparison between the angles of the first and second dolly from test one and three with a 3s delay applied to the first dolly on both.

The RMSE for the first test run was 4.37 and the third run is 6.52.



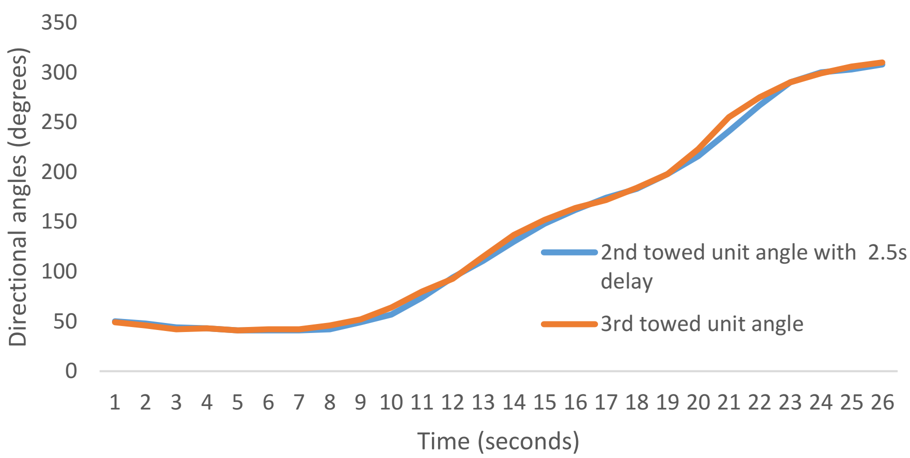
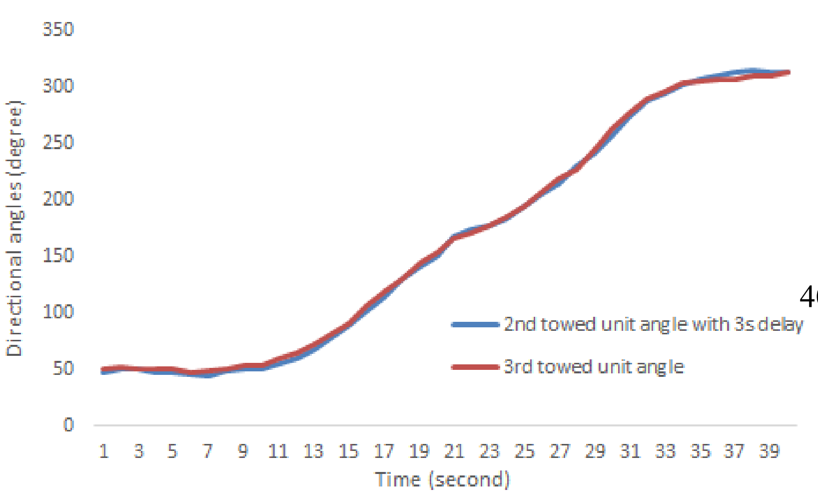
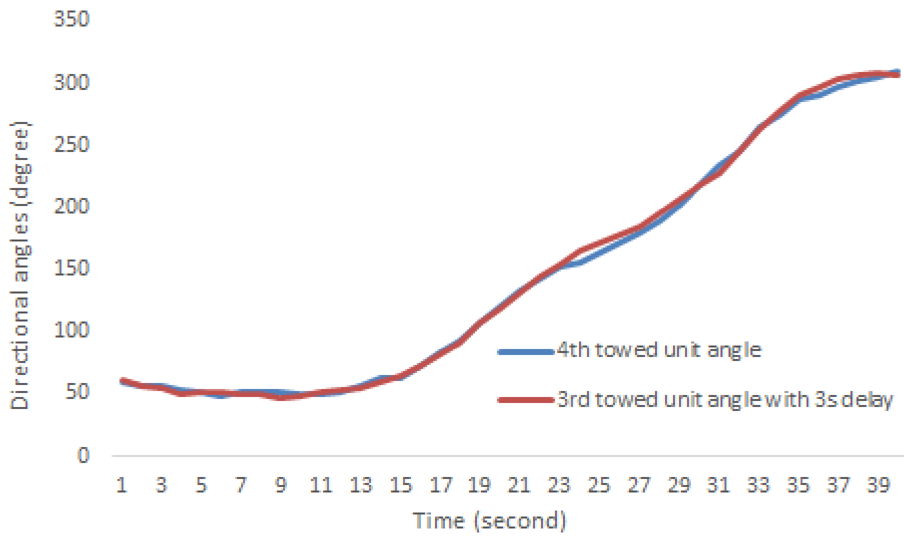


Figure 4.12 Comparison between the angles of the second and third dolly for test one and test three with a 3s and 2.5s delay applied respectively.

The RMSE for the first test run was 3.21 and the third run is 4.62.





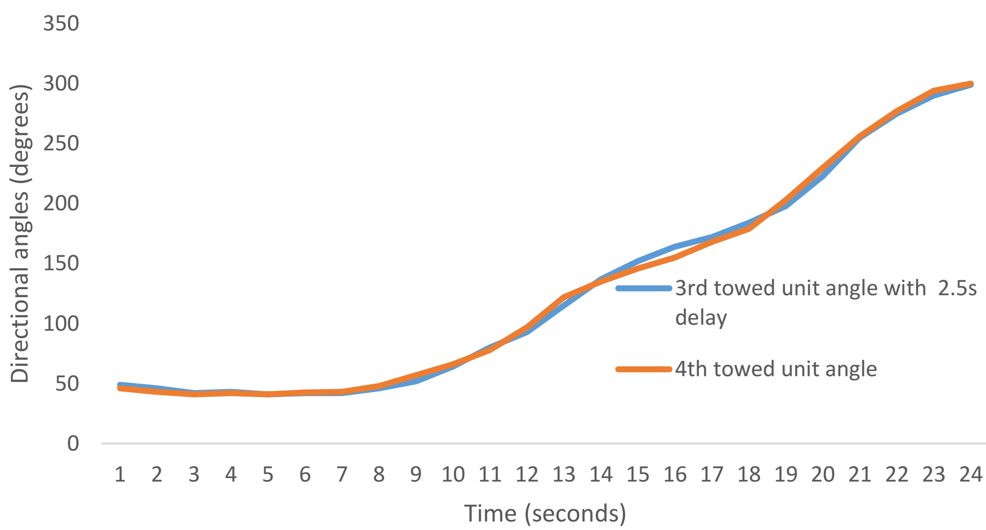


Figure 4.13 Comparison between the angles of the third and fourth dolly for test one and test three with a 3s and 2s delay applied respectively.

The RMSE for the first test run was 3.85 and the third run is 3.99.

4.4 Summary of Validation

From Figures 4.12-4.14 the curves almost matched perfectly when compared connecting vehicles are compared, the RMSE values also decreased by a noticeable factor a summary of which can be seen in Figure 4.14.

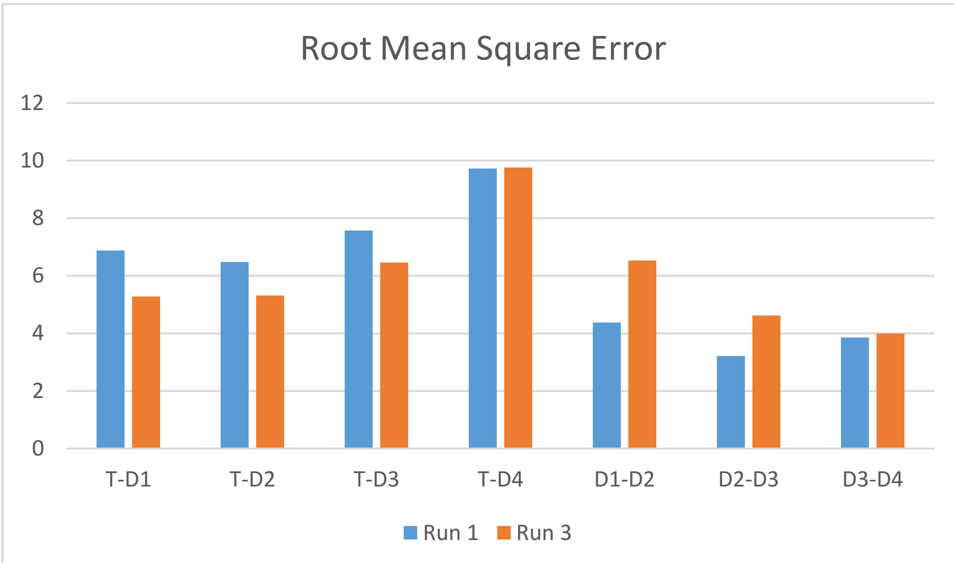


Figure 4.14 The RMSE values compared to each other. T is the tractor and each D represents a different Dolly such as T-D1 is the time delay on the tractor for the first dolly.

Notice the general decrease in error when the dollies are compared to each other instead of the tractor.

This confirms that each dolly follows the vehicle directly in front of it with only a small deviation. With the observation formed from all of the figures in this section the following conclusions were developed.

(1) The assumption of neglecting "off-tracking" which hypothesized that each sequential dolly will follow the previous one in the same order of angles at a

slightly delayed rate is correct, leading to the presented predictive of angular transferring is possible and would not lead to an uncontrollable amount of error.

(2) The size difference between the tractor and the dollies is the likely cause of the deviation between the tractor and first dolly which also accounts for the higher error in the later tractor dolly comparisons. The change in size leads to the tractor and dollies having different turning radii.

(3) The deviation in the fourth dolly is most likely due to the buildup of “off-tracking” error through the angular transferring process.

Similar observations and conclusions were found through investigating the aerial images from the other test runs. Despite this, it should be noted that time delay is sensitive to operating speeds of the tractor-dolly system, for the purposes of this thesis, and the phase of testing it is based on, the average operating speed for an airfield tractor-dolly system is approximately 5mph, with only slight change variation.

CHAPTER V

APPLICATION

The primary objective of this thesis was to present a dynamic model that could generate a relatable shape of a tractor-dolly system. The model must be able to produce the shape, or polygon model at any instantaneous time during operation based on instantaneous operating variables. If accurate variables, i.e. the directional angles, can be determined for the tractor and predicted for the dollies the polygon should closely reflect the shape of the actual vehicle system at any time. This polygon is limited in scope due to the neglecting of "off-tracking" which is more noticeable at the dollies furthest away from the tractor. Due to the intention of this work to lead to collision avoidance error must be accounted for whenever possible. To correct the error a solution was presented in the form of increasing the size of the polygon to provide a buffer.

In order to display the how to apply the buffer to account for the error in the polygon model, a high-error case from test run 1 was chosen. The high-error case has a predicted angle that can be seen in Figure 5.1, the yellow outline represents the polygon traced over an aerial photo. Notice at the end of the train in Figure 5.1 the polygon of the fourth dolly is off by a small, but noticeable margin when the it is strictly based off of the dimensions of the actual vehicle system. The aforementioned buffer was applied into the model to correct the error through increasing the width of each vehicle in the polygon by a multiplier of 2.5 which is shown in Figure 5.2. Due to the maneuver in Figure 5.2 being one of the highest error cases in the prediction of the tractor-dolly system and the increased size of the polygon covers it in safer scope it can be assured that the polygons can envelop the entire system at any time.

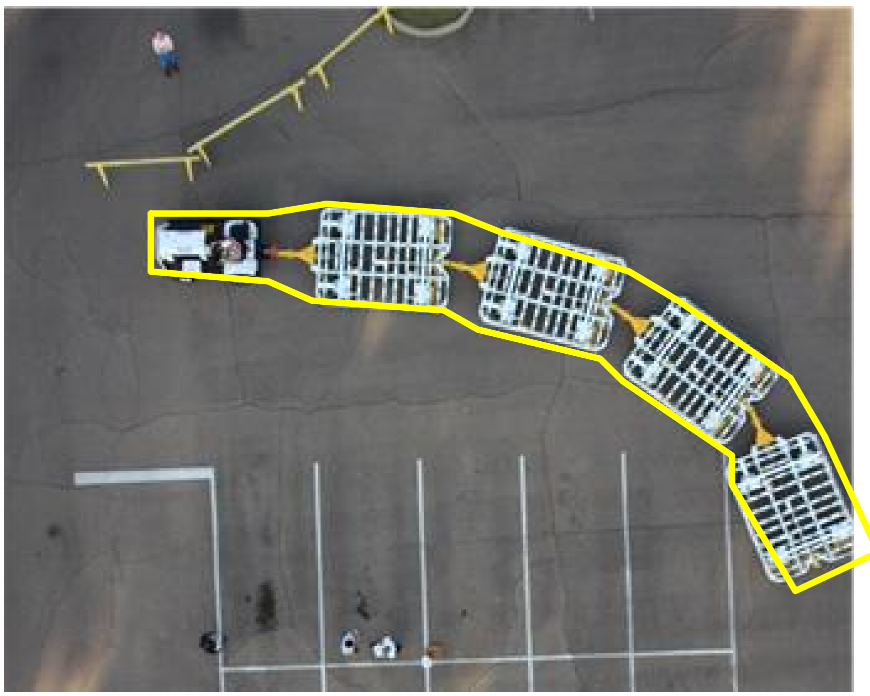


Figure 5.1 Polygon representation overlaid onto an aerial photo.

Notice the slight deviation on the fourth dolly.

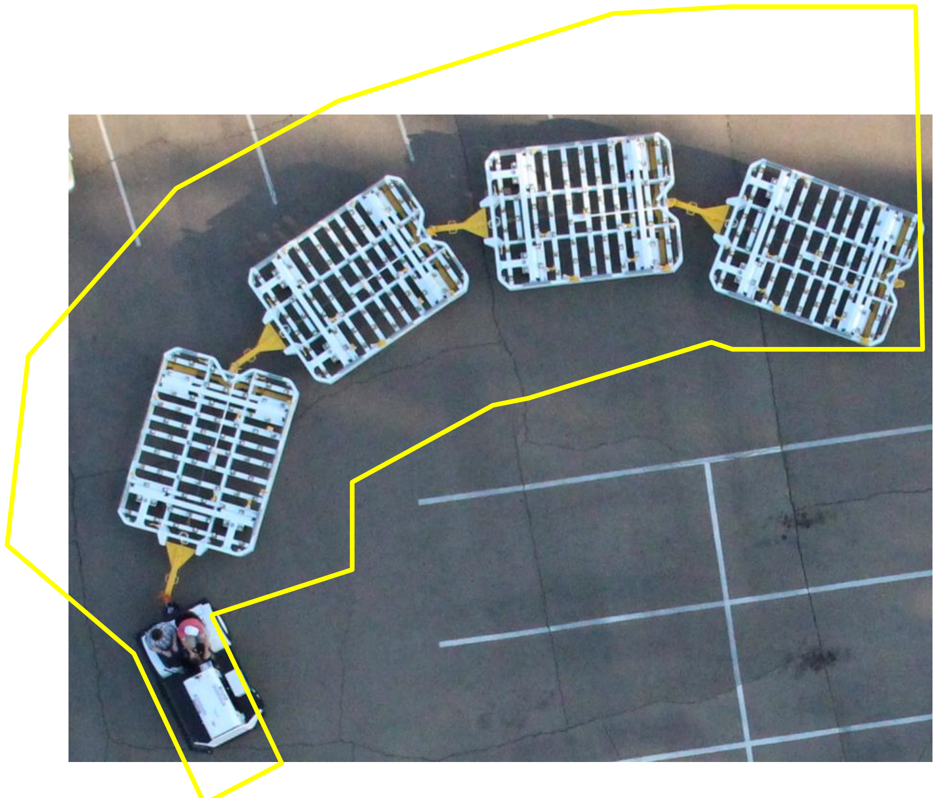


Figure 5.2 Polygon envelope with a 2.5 times the width applied to the shape.

CHAPTER VI

CONCLUSION

The previous works referenced in this paper primarily focused on large tractor trailer systems or single car single trailer and did not necessarily focus on collision avoidance through predictive pathing. However the dynamic involved in these works were fundamental to the development of the model. Despite previous work being similar in idea the problem at hand required a model to be developed to predict complex 5 part system.

This thesis presents the framework of a dynamic model intended on drawing instantaneous shapes to represent an actively running tractor-dolly system. The dynamic model began with a state space model to the directional angle of the tractor; an assumption that when turning, the dollies will follow in the tractors path through its same directional angles thus ignoring off-tracking; and a polygon model that uses the previous parts to create a representation of the tractor-dolly system.

To validate the dynamic model, a series of field test were conducted. Evaluating the results of the field test showed that the state space model can accurately determine the angular direction of the tractor at any time. If the directional angles are correctly deduced then that leads the polygon model to accurately representing the tractor. Using the assumption of the dollies following the tractor along the same path leads the polygon into accurately representing the trailing vehicles as well, if the correct time delay is applied. It should be noted that this study for the first time verifies that off-tracking is negligible if the tractor and its dollies are of a similar size leading to a similar turning radius. The similar size between the dollies led to very little error in this prediction method. However when the angles are being derived from the tractor, which is smaller than the dollies, there is a small yet noticeable amount of error in the prediction of the fourth dolly. To account for this error the polygon model was adjusted to a width of 2.5 times actual size to allow for a reasonable buffer. In future work on this system two improvements can be made to eliminate the error in the fourth dolly: 1. Evaluate and re-program the controls and sensor system to calculate the instantaneous radii of the tractor to correctly calculate the individual paths of each towing vehicle, or 2 install a second IMU on the 3^{rd} or 4^{th} dolly allowing for instantaneous angles to be registered, thus giving a more accurate prediction model.

The presented thesis in its dynamic model was validated with a tractor system that involved one to four dollies, but it can be modified to any vehicle system that contains a similar shape or function. To further improve the model a suggested future work is to test the system on an airport or larger parking lot with its full sensor array to allow for empirical data to collected for refinement of the system. The major body of this work has been published in the SAE world congress [12].

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