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ScienceDirect

Procedia Manufacturing 51 (2020) 164–170

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)
15-18 June 2021, Athens, Greece.

Study of the kinematics of a high-course steering system

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Abstract

In a context of mobility disruption, due to the accelerated growth of new technologies and sustainability policies, a new class of vehicles is emerging, depending on the type and its function, requiring new technologies suited to its goal. The autonomous modular platforms emerged, in this scenario, to reduce the time of placing electric vehicles on the market, the complexity of the supply and the total cost of production of the vehicle. To facilitate and adapt maneuverability of vehicles to the future challenges of mobility, this paper presents the study of different solutions for a steering system integrated in a modular platform already existing, that enables the vehicles 360° and 90° movements. The difficulty of developing this project is to find a mechanism that meets all kinematic requirements, without compromising the other systems of control and stability of the movement. Thus, considering the parameters of traction and suspension, possible solutions are developed, subsequently tested with the use of the SolidWorks software. Finally, it is concluded that of the solutions tested, the most satisfactory is the one that presents the best kinematic characteristics allied to the smallest course, despite being one of the solutions with more components.

Keywords: Autonomous vehicles; Mobility; Modular Electric Platform; Steering system.

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1. Introduction

Competitiveness and productivity beyond its correlation are two indicators of success in the industry. With the shift in the mobility paradigm and growing environmental concern, the automotive industry gains new challenges and opportunities [1-3]. CO_2 emissions and other greenhouse gases are one of the biggest environmental concerns with an impact on the automotive industry [4]. Electric mobility is seen as a technological solution for reducing these emissions and increasing energy efficiency [5,6]. In this scenario, and considering performance and safety factors, autonomous modular platforms have emerged to reduce the time of placing electric vehicles on the market, decreasing the complexity of supply and the total cost of production of the vehicle [7]. In short, this type of platform emerged in order to make the production of electric vehicles more sustainable.

The present work is inserted in the development of a module adaptable to an existing autonomous modular platform that confers the 360° movements (rotate on itself) and 90° (lateral displacement), to facilitate accessibility and displacement in situations of difficult maneuverability. The main objective of the developed system is to make the platform more appealing in the market. The insertion of these types of movement is relevant for some types of vehicles where the platform can be used. For example, emergency medical vehicles, urban cleaning vehicles, freight vehicles, among others [8]. Also, this type of movements can be useful in vehicles inserted in a new mobility paradigm, for example mobile support structures vehicles for shared and electric mobility.

The article focuses on the steering system, as it is the main wheel control system, keeping in mind concepts of green manufacturing. Initially, a literature review of steering systems is carried out. Then, in the methodology, all assumptions and design parameters are presented. Also, in the methodology, the kinematic tests carried out using SolidWorks software are explained. Finally, the results are presented and analyzed, ending with the conclusions obtained.

10.1016/j.promfg.2020.10.024

2. Literature Review

The steering system is responsible and crucial for the vehicle to accurately follow the course established by the driver. It is also through it that the driver receives feedback if the vehicle responds predictably and reliably [9,10].

According to Harrer *et al.* [11], developers of steering systems, therefore, have to consider numerous demands and tasks to achieve a customer-friendly design:

- Sufficiently low steering wheel torques and a narrow steering wheel angle required for parking;
- Ease of movement, sensitivity, accuracy, a high degree of directional stability, sufficient immediacy and spontaneous responsiveness;
- Pronounced road contact, the responsiveness of tire-road adhesion;
- Automatic return to the central position, good centering, stabilizing behavior under any driving situation;
- Compensation of disturbance variables stemming from road surface irregularities, drive, braking, and irregularities of the tires;
- Adequate absorption to suppress self-induced vibrations of the vehicle;
- Compliance with the crash safety requirements and passenger safety regulations;
- Low energy consumption;
- Sufficiently low noise level;
- Vibrational stability (no self-induced vibrations);
- Low wear and low maintenance over the entire vehicle life cycle.

Kurebwa and Mushiri [12] recently developed a new concept of steering based on the Toyota's Variable Gear Ratio Steering system combined with an electric power steering system, trying to enlarge the usability of SUVs (Sport Utility Vehicles). The main goals of that work were the fuel consumption reduction and the space optimization, keeping the stability of the vehicle at high-speed and improving the maneuverability at lower speeds. The steering control also was explored by Prasad and Ma [13] trying to optimize the control in six-wheel independent drive vehicles. In this case, and considering that this kind of vehicles presents a distributed independent drive differential speed, the authors used a theoretical hierarchical control allocation based on a quadratic programming mathematical technique able to solve the problem and distribute in a proper way the control by the wheels, taking into account relevant factors such as wheel slip limitation, real-time torque distribution and wheel failure. The control strategy assumed ensure a better working conditions in normal use, and avoids handling failure of the wheels. A new differential steering control system for an electric vehicle with four wheels was also studied by Li et al. [14]. For this, the MATLAB / Simulink software was used to establish the dynamic model of the vehicle and the differential direction. In order to establish the yaw rate, which is controlled through a differential torque controller, a vehicle model containing two degrees of freedom was selected and, based on that, a double closed loop control system based on the control was proposed of the structure in a sliding way to improve the stability in use. A torque compensation controller for engines was also added in order to solve the problem of power loss in the steering. The results show that the control system can effectively regulate vehicle states to improve stability. Through simulation it was verified that the control strategy presents a good performance, even in complex driving conditions.

2.1. Steer by Wire

Steer-by-Wire (SbW) was developed as a revolutionary technological innovation, with main application in the automotive industry. It may be noted that a SbW system is usually made up of the following units: (a) electronic control unit, (b) steering assistance motors and (c) actuators that are capable of acting out the actions normally attributed to the mechanical steering column of a car. However, before these systems can be applied in the automotive industry, it is necessary to have perfect confidence in their reliability and fault tolerance, as they are a critical component in the safety of vehicles and their passengers. There are many studies reported in the literature on fault detection and isolation, but fault diagnosis and fault tolerance in SbW systems has not received the necessary attention. The redundancy of these systems is completely indispensable. Thus, the study of how the system can circumvent any failure has been the subject of study, but the state of maturity of the system is still not enough to be perfectly reliable on the part of the automotive industry and, only very recently, with electric vehicles and autonomous driving, this subject has been receiving more attention by researchers [15]. In the SbW system, the driver's steering effort is transferred electronically to a system that is not physically connected behind the wheel. Thus, the greatest advantage of this system is the flexibility and construction space that allows. The problem with this system is that even with the use of electrical redundancies, the mechanical backup may be necessary to protect against the loss of function of the system if the vehicle experiences a significant electrical interruption. This technology is restricted to vehicle projects that take significant benefits from this technology because, to achieve an acceptable level tolerant of failures, the SbW system compared to current mechanical systems has costs significantly higher [16]. Moreover, concerns about the safety and reliability has remained. Thus, in order to overcome some of these problems and based on a report issued by the National Highway Traffic Safety Administration (NHTSA), and taking into attention a recent revision of the ISO 26262:2018 standard [17], Huang and Li [18] studied and proposed a new fail-operational architecture for the SbW system. The safety and reliability of the new fail-operational architecture was checked using quantitative fault-tree analysis and state transition diagrams, showing that this architecture responds positively to the concerns usually taken into account regarding this system.

Indeed, the most recent studies have been essentially focused on the reliability and reliability of systems, that is, on control. However, the dynamics of these systems is also very important, with studies dating back to the beginning of the 21st century, which sought to identify the best conditions for action, because geometry and design need to pay more attention to details in the observability and controllability of the vehicle. Laws et al. [19] concluded that the design of systems for the individual drive of the wheels has very different characteristics from those that are normally taken into account in the design and dimensioning of traditional steering systems.

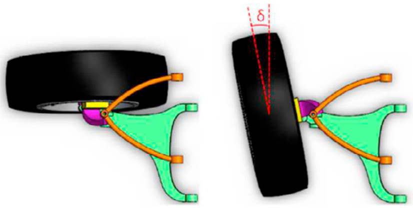
3. Methodology

The steering system, despite being the main wheel control system, is dependent on other wheel control and stability systems. The project considers the use of engines on the four wheels, with the built-in braking system and the use of a Double Wishbone suspension with the parameters shown in Table 1. The use of motors on the wheels makes it easier to independently control the wheel. In addition, it allows the elimination of components creating useful space for the study of the steering system. The Double Wishbone suspension allows flexible configurations that also become an asset for the development of the steering system.

Table 1. Suspension system parameters.

Roll center height	130 mm
King pin inclination	13°
Scrub radius	50,38 mm
Camber	-2°
Caster	4°
Caster trail	22,83 mm
Damper motion ratio	0,65

The dimensions considered for the vehicle are those shown in Table 2. In this way, the angle of sweeping required for the wheels is approximately 102°. The sweeping angle is determined by the extreme positions of the wheel (Fig. 1). One of the positions is defined by the lateral movement without maneuvers (90° - Fig. 1a). This position must also be defined to allow the 360º movement of the platform. The other position is defined by the turning radius (Fig. 1b). To determine the turning radius (Equation 1), curves with a radius of 15 m were considered.



(a) (b)

Fig. 1. Extreme wheel positions: (a) lateral movement; (b) turning radius.

Table 2. Vehicle dimensions.

Length	4750 mm
Width	2110 mm
Height	2650 mm
Track	1810 mm
Wheelbase	2900 mm
Minimum ground clearance without load	200 mm

$$\tan(\delta) = \max\left(\frac{L}{r \pm \frac{T}{2}}\right) \tag{1}$$

In Equation 1, L is the wheelbase, T is the track, r the radius of the curve and δ is the turning radius. T, L, and r in meters and δ in degrees.

The proposed objective requires, in addition to the high angles of sweeping, an independent control of each wheel. The project makes it impossible to use conventional mechanical connection systems. Thus, the steering system used must be by wire type.

The direction system parameters were defined only using CAD software. To this end, package aspects were considered and kinematic studies were carried out. This method allows the realization of several iterations and ensures that the parameters of the other systems are met. For moving components, it is considered that the absence of interference corresponds to a clearance equal to or greater than 10 mm.

Regarding the mechanism that induces movement, two hypotheses were considered, the use of electric linear actuators and the use of pinion rack mechanisms. It was decided to choose the solution more favorable to the rest operating system of the wheel and, indirectly, its selection part of the iterative process. It is known that there must be a mechanism of these per wheel and that, regardless of the mechanism chosen, the smaller the course the better. The possibilities of fixing the actuation mechanism must be considered in its positioning due to the importance of the stability of the wheel control both in terms of hardness and mechanical resistance.

The iteration process is conditioned by the kinematic studies carried out. The steering mechanism must pass in three tests:

- The derivative of the relationship between the wheel angle and the actuator stroke must be less than 0,9;
- The height variation of the wheel may not cause a variation of its angle greater than 1°;
- The first test should work for the wheel height variation. In this way, the first test must be valid from positions -100 mm to 100 mm, concerning the base position (zero), with the verification carried out every 10 mm (positions -100, -90, -80, …, 90 and 100 mm).

The first test indicates, if it fails, a deficiency in the transmission of movement between the actuator and the wheel. The value 0.9 is used in the design of autonomous vehicle steering systems as a limit to guarantee a good transmission of movements. The failure of the second test can have two origins: if the resulting graph is straight, is related to the angle that the direction lifter makes with the actuator in the neutral position. If the chart is a parable, the problem is the length of the direction lifter. The variation in wheel height should not have a significant influence (above 1 °) on the wheel angle. The third test is a safety check of the previous two whereas the angle of scanning of the wheel is high. Thus, the following solutions were tested iteratively:

- A linear actuator, without angle, with only one steering rod;
- A linear actuator with angle direction with a rod (Fig. 2);
- A linear actuator, without angle, using three steering rods (inspired by the ZF solution [20]);
- Circular rack mechanism and steering rod (Fig. 3);
- Circular rack mechanism and three steering rods (Fig. 4);
- Angle linear actuator and three steering rods.

The solutions presented were emerging throughout the studies to find a low-course solution that meets the requirements/tests and allows a simple architecture with the fewest components possible. It should be noted that the wheel control systems prevail at the last aspect.

The first two solutions presented are those with fewer components. In this way, they are the ones that allow more configurations. The second solution (Fig. 2) appeared to reduce the travel of the actuator without compromising the transmission ratio. The third solution, inspired by the ZF solution, appeared to combine the reduction of the stroke with the kinematic results because, in the tests carried out with the first solutions, an inverse relationship was found between the stroke and the ratio of movement transmission. The fourth solution (Fig. 3), is a compact solution, with fewer components (compared to the third) and centered on the movement transmission ratio. The fifth solution (Fig. 4) is a mixture of the third and fourth solutions to assess how the kinematic tests are affected. Finally, the sixth solution emerged to verify the influence of the direction of the actuator stroke on the third solution.

All solutions presenting a linear actuator as the actuation mechanism of the wheel can be improved, replacing that system by a pinion rack mechanism driven by an electric motor. This replacement can be considered because, while a pinion rack mechanism has approximately the length of the necessary course, in the actuator, the course represents 2/3 of its length.

There are settings where kinematics is different on each wheel. This happens in situations where it is not possible to place the mechanisms of action of the wheels in a symmetrical position without interferences.

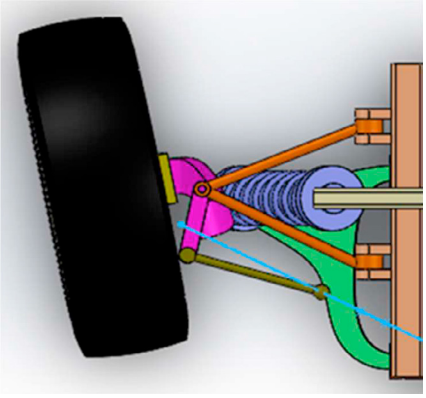


Fig. 2. Configuration example with solution 2.

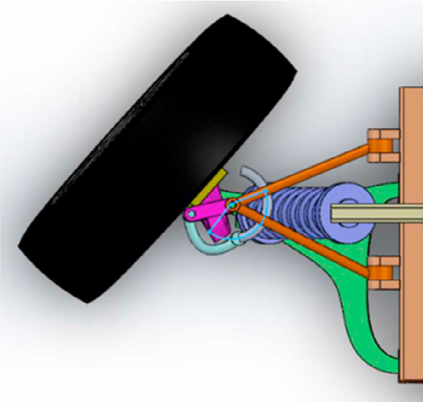


Fig. 3. Configuration example with solution 4.

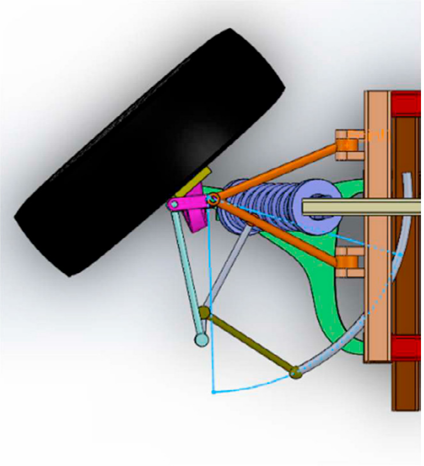


Fig. 4. Configuration example with solution 5.

Numerous cases have been tested within the solutions presented. The variation of the action plan, the location of the point of operation in the axis sleeve and the positioning of the mechanism of action are some examples of the variations made in the various configurations of the solutions presented. The influence, for example, of how the position of the mechanism of action varies has very different kinematic results for each of the solutions. Factors like this hinder the iteration process.

4. Results and discussions

Many of the cases previously explored were eliminated because they did not meet kinematic requirements, such as circular rack solutions. This solution was created to decrease stroke acquiescent to a better relationship between actuator stroke and wheel angle. The mechanism was successful in this regard, however, the variation in wheel height had a great influence on the angle. There are solutions that, although tested, had problems beyond kinematic issues. The solutions using circular rack had gears positioned in very exposed places and difficult to isolate. Other cases were not even tested because throughout the movement they presented interference between components.

Finally, the solution with the best results was the use of linear actuators combined with a mechanism with three steering rods (Fig. 5). Despite being one of the tested solutions with the most components, it has the best kinematic characteristics combined with the shortest stroke, 208 mm.

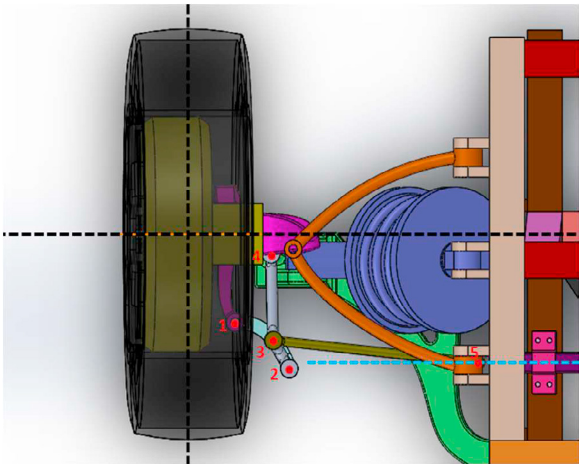


Fig. 5. Solution for the steering system.

The points represented in red in Fig. 5 represent the connections of the steering system. Point 1 represents the connection between the stub axle and tie 1, point 2 the connection between tie 1 and tie 2, point 3 the connection between tie 2 and tie 3, point 4 the connection between the tie 2 and the lower suspension arm and finally, point 5 the connection between the tie 3 and the actuator. Points 1, 2, 3 and 5 are label-type connections, while point 4 only allows rotation in the plane. Also, in Fig. 5, the blue line represents the direction of travel of the actuator.

In the base position (Fig. 6), the actuation plane is positioned at 337.40 mm relative to the ground. The remaining dimensions are shown in the Table 3 concerning Fig. 6.

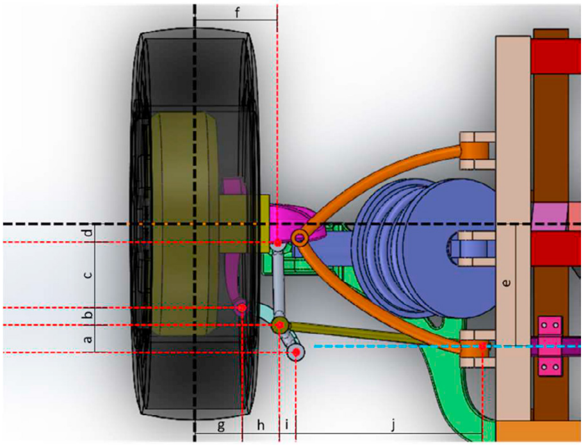


Fig. 6. The positioning of the solution for the steering system.

Table 3. Dimensions regarding Fig. 6.

a	46,03 mm	f	141,16 mm
b	29,71 mm	g	80,73 mm
c	111,96 mm	h	65,08 mm
d	32,88 mm	i	28,13 mm
e	210,30 mm	j	320,30 mm

The definition of the steering system implied changes in the suspension system, namely the change in the geometry of the shock absorber which consequently caused changes in the upper suspension arm. The lower suspension arm has also changed since it has one of the steering system's supports. However, as intended, the parameters shown in Table 1 have not changed.

The relationship between wheel angle and actuator stroke is shown for positions -100, 0 and 100 (Fig. 8, 7 and 9, respectively). And the influence of height variation is represented in the graph of Fig. 10. For positions -90, -80, -70, -60, -50, -40, -30, -20, -10, 10, 20, 30, 40, 50, 60, 70, 80 and 90 mm, the graphs of the relationship between the wheel angle and the actuator are not shown because, as no anomaly is recorded, they are not relevant.

As can be seen from the graph in Fig. 7, the derivative is within the stipulated limits (less than 0.9) and the relationship between angle and stroke has high linearity, which means that there is good transmission of motion between the actuator and the wheel.

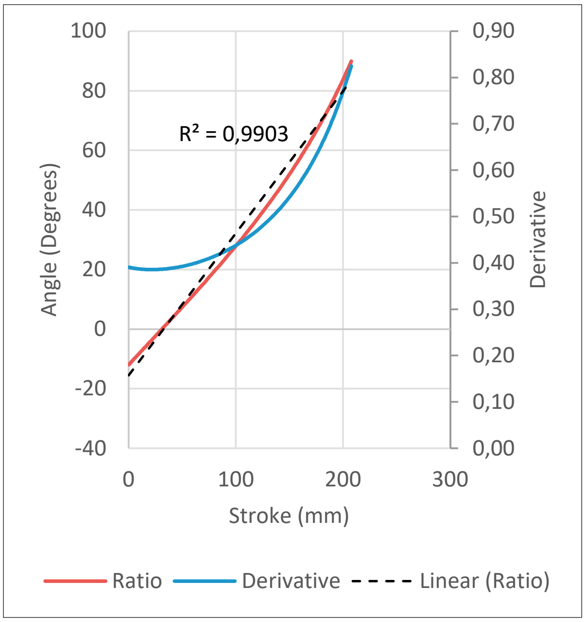


Fig.7. Relationship between wheel angle and the stroke of the actuator, position 0 (zero).

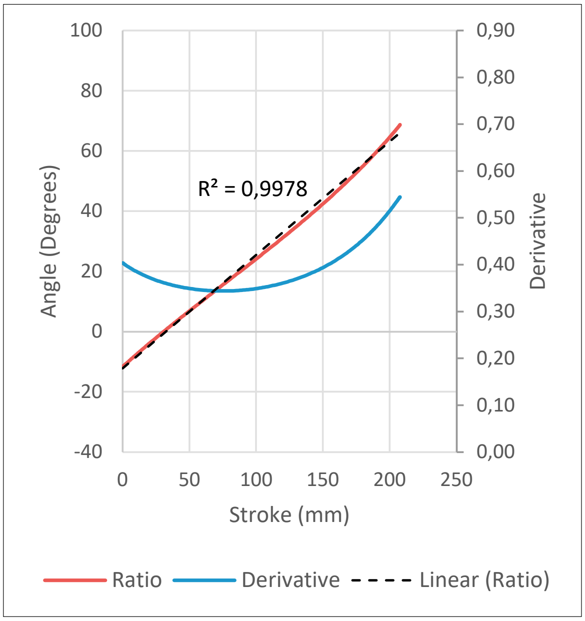


Fig.8. Relationship between wheel angle and the stroke of the actuator, position -100.

The graphs in Figs. 8 and 9 show that the analysis performed in the neutral position is still valid with wheel height variation. The graph in Fig. 10 shows that there is no significant influence between the wheel height variation and the angle, since the variation presented is less than 1°.

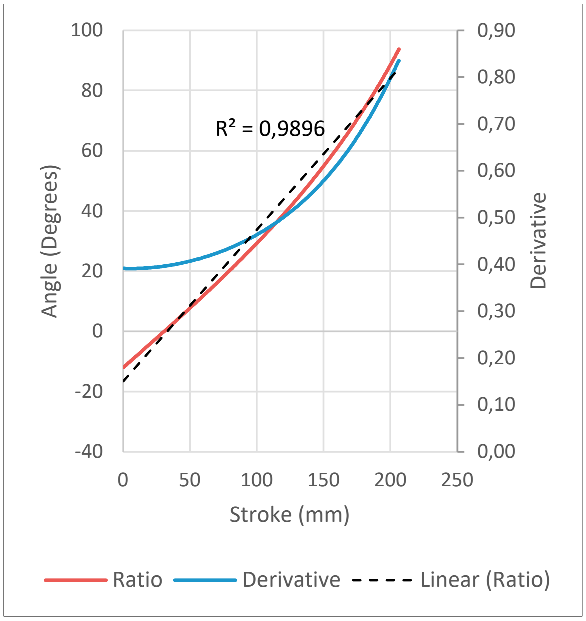


Fig.9. Relationship between wheel angle and the stroke of the actuator, position 100.

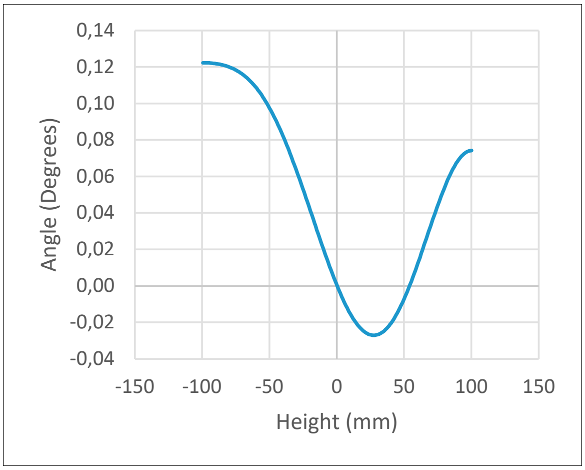


Fig.10. Influence of wheel height.

5. Conclusions

The work developed explores several solutions considering all the requirements and constraints of the project. This is an iterative work, time-consuming with several configurations within the possible solutions presented.

Among all these solutions, the selected one is the one that presents better kinematic characteristics combined with the smallest course. The course, of 208 mm is the smallest found for the scanning of the wheel of approximately 102°. The great disadvantage of the final solution is the number of components, namely rods needed for the transmission of movement.

Reliability and development of the way the steering system is actuated should be something to consider for the practical application of the system, i.e. the reliability of the SbW systems. In short, considering the tests performed, a viable solution with excellent kinematic characteristics was found.

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