2010 IEEE/ASME International Conference on
Advanced Intelligent Mechatronics
Montréal, Canada, July 6-9, 2010

Biologically Inspired Telescoping Active Suspension Arm Vehicle: Preliminary Results

Gavin D. Kenneally[1], Luis Rodrigues[2]

[1]Department of Mechanical and Industrial Engineering, Concordia University

[2]Department of Electrical and Computer Engineering, Concordia University

***Abstract*. This paper proposes a new type of active suspension system for road vehicles. The paper addresses the design and analysis of the vehicle's suspension with the intent of later integrating this work into a fully functional prototype. The work presented here builds on a previous prototype built by the first author by adding telescoping suspension arms whose displacement can be actively controlled. This flexibility enables the vehicle to become more compact, or more stable depending on the situation. The advantages of the vehicle designed in this paper are twofold. First, it can potentially be used in several rough landscapes, such as other planets or debris caused by natural disasters. Second, the vehicle has the potential to be used in emerging countries where the infrastructure has not yet evolved to the point of acceptable performance for conventional vehicles.**

I. Introduction

THE work reported in this paper represents a novel concept in the field of active suspension systems. The main idea is to control not only the position of the suspension arm but also its length, which enables better performance over a wider range of terrain. The width of the vehicle will be actively controlled and changed on-the-fly, resulting in a system that can range between different widths within a short period of time (Figure 1). As cars continue their penetration in the most remote regions of the Third World, they will often be expected to replace their predecessors (in many cases, work animals or even hand carts). They also will be expected to work on highways while moving between rural areas. That is to say, a vehicle will have to function in the cramped confines of a marketplace, the harsh, bumpy terrain leading to remote dwellings, and modern highways connecting towns.

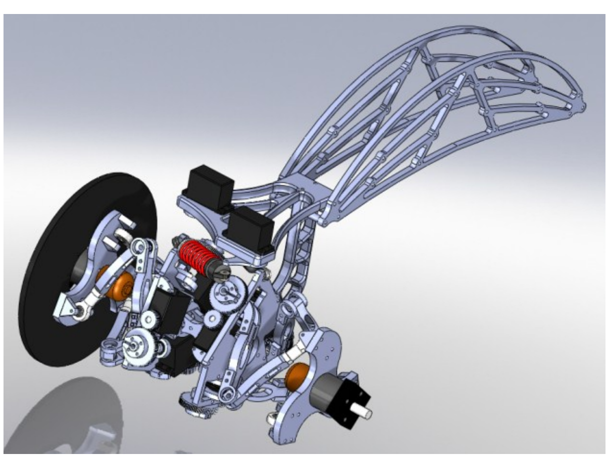

Fig. 1. Suspension arms in prototype vehicle.

Manuscript received May 3, 2010. This work was supported in part by NSERC and CIADI

Suspension in a vehicle is designed to minimize the effect of road disturbance (physical interference) on the chassis (and thus the passengers, or even sensors if applicable) as well as maximizing the contact between the tires and the road to increase cornering and braking performance. This scenario can be quantified through a mass spring model where the ideal frequency response is said to be critically damped, meaning that the time required to bring the system back to equilibrium is minimized. The problem with the application of this model is that it works on the premise of overcoming a force that is constant, which is obviously not representative of reality. While a conventional suspension system may be optimized for a given force, it would be impossible for it to respond perfectly to a range of magnitudes. Current active suspension solves this problem by minimizing disturbances through a control system to achieve what is effectively a closer approximation of a critically damped response over a much wider range of forces.

While conventional approaches have proved to be very effective at eliminating disturbances that are transmitted to the system, they fail to provide significant advantages when centrifugal forces are considered. These forces act radially outwards proportionally to the square of the object's velocity, and in inverse proportion to the radius of the turn. This is the cause of what is referred to as "body roll" in a car, and is felt to some degree every time a vehicle goes through a corner. Nature has been dealing with this phenomenon for a long time, which is why animals that corner at high speeds, such as the cheetah, have developed coping mechanisms such as sprawling outwards during cornering. This coping can be generalized and further explained with the help of a diagram shown in Figure 2. Only the centrifugal force and the normal forces will be considered to best analyze the problem. The resulting force will produce a moment. If the moment relative to a given point cannot be eliminated, the body will roll relative to that point. When the animal is stationary, both legs carry the weight evenly. However, when the animal starts a turn, the normal force on the outer leg increases up to a maximum

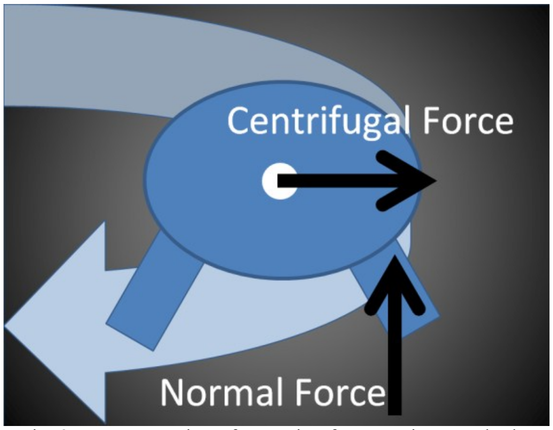

Fig. 2. Demonstration of cornering forces acting on a body.

value equal to the animal's weight. In order to compensate for the large centrifugal forces generated by high speed cornering, the outer leg (or wheel) must thus be placed significantly further from the body compared to when the vehicle is going straight. It is with this natural phenomenon in mind that the idea of telescoping suspension arms is proposed in this paper.

The main objective is thus to design and analyze a small scale, working prototype, with the intent of building and controlling the vehicle in the future. This will be a "proof of concept" and is expected to become a good platform for testing control algorithms. The design was performed using CAD (Computer Aided Design) and calculations based on technical documents of existing parts. The analysis will be done by considering the mechanics of the system including both static and dynamic models analyzed with the help of FEM (Finite Element Methods). Manufacturing will be performed using a CNC (Computer Numerical Controlled) milling machine. A PID (Proportional, Integral, Derivative) control system will be implemented using an ARM Cortex M3 microcontroller in the near future.

It should be noted that this article focuses nearly exclusively on the design and analysis of suspension arms, with very little attention to the chassis of the vehicle. This is not an oversight but a testament to the modular nature of these telescoping arms. The actual performance characteristics and shape of the chassis do not affect the successful operation of the telescoping arms. This means that a wide array of specific chassis can be accommodated, increasing the utility of this platform. A very simple parallel vertical plate chassis will be used in this first "proof of concept", but more advanced variations can be found below in section III.

II. CONTRIBUTION

While this project is considered evolutionary as opposed to revolutionary, there are no directly competing systems implemented today, to the best of the authors' knowledge. The contribution can therefore be classified in two categories: a comparison against conventional active suspension systems that function based on shock preload, [1][2][3] and newly developed concepts that are still in the research and development stages of production.

When considering active suspension systems that are used in vehicles today, it is important to make the case for this prototype being not only a potentially better solution, but one that is also necessary. As the world population density increases, and as more people need and demand vehicular transport, the dynamics of how vehicles look and are expected to perform must change as well. The "old model" of active suspension relies on the control system to merely smooth noise and disturbances, and the stability of the vehicle is due to its significant width-to-length ratio. With a more active system, however, it would be possible to maintain the same levels of stability, necessary in extreme cases by elongating the suspension arms. The compact dimensions of the vehicle when cruising at low speeds would be essential as cars will be allocated less and less space in the future. Given these likely socioeconomic trends, an active cornering system can therefore be considered highly desirable.

With this in mind, it is imperative to consider all possible solutions that would provide the compensation that has been deemed necessary. The most complete prototype to provide such a solution was unveiled at the 2009 Tokyo Auto Show, called the Nissan Land Glider [4]. This concept vehicle uses vertically pivoting suspension arms to lean while cornering, in a manner similar to a motorcycle. This system however results in a variable track length, a characteristic that will be discussed below in greater detail, followed by a direct comparison between the mechanics of the two systems. Furthermore, the Land Glider is only designed to counter centrifugal forces, which does not help the vehicle overcome obstacles such as rough terrain.

Variable track length is due to the fact that the suspension arms use their actuation in the front/rear vertical plane to achieve their stability, rather than working in the side to side plane where the stability benefits are more apparent. As can be seen in Figure 3 when the wheels separate to effectively lower one side of the vehicle (the red arrow) the track length of the car (blue arrow) is affected as well. This adjustment has the distinctly negative repercussion of completely altering the stability characteristics of the car every time it has to go through a corner. Furthermore, the steering response will become less predictable as the left and right wheels are no longer rotating on a common axis.

An effective comparison would be to study the dynamics of the proposed prototype and the Nissan Land Glider vehicles as they go through a tight corner and see which can sustain a higher theoretical maximum speed (assuming perfect cohesion between the tires and the road).

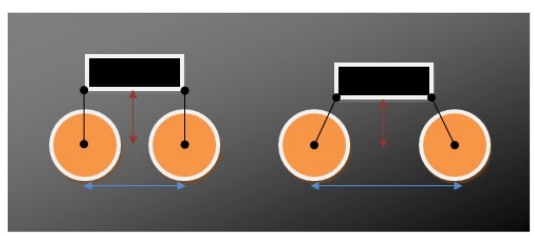
Fig. 3. Figure demonstrating variable track length.

Conveniently, the outer dimensions of the Land Glider are given, as well as its maximum rotation of 17 degrees. For the case studied in this paper, direct scaling (by width) will be used to match the dimensions of the prototype with its full scale counterpart. Since the position of the centers of mass cannot be easily obtained, they will be assumed to be the same for both vehicles, at 30% of the height (although realistically, it will most likely be lower in the prototype's case due to the mechanical components and actuators built into the suspension arms). The scenario that will be considered is the "tipping point" or the point at which the vehicle is still stable, but beyond which any additional forces would cause instability. This situation is represented by a moment calculated at the innermost point of the vehicle cornering being non-zero. The result of the calculations was that if the vehicles were travelling around a corner with a 5m radius, the Land Glider would reach its tipping point travelling at 29.9 km/h whereas the prototype developed here would be stable until 38.5 km/h. These results can be obtained by taking a moment about the point at which the center of mass intersects the ground if projected vertically:

$$L_{extended\ arm}\ m\ g = Y_{COG}\ m\ a_{centrifugal}$$

Where $L_{extended\ arm}$ is the length of the arm at its outermost position, and Y_{COG} is the height of the center of gravity. This improvement is a clear indication that this concept is worth investigating and is highly desirable since the vehicle stability considering acceleration can be effectively improved by the differences in velocities squared.

III. METHODOLOGY

The methodology for this project can be divided into five main stages: design, construction, synthesis of control system, closed-loop analysis and testing. The first consideration is the overall *design* goals. The following design constraints will govern the dimensions and capabilities that the prototype will have:

- Maximize ratio of expanded arm length over contracted (currently 3.83)
- Maximize under chassis clearance
- Center of mass assumed at150mm from the ground
- Expected cornering acceleration of 3g

Under these design constraints, the vehicle will have to extend each arm by roughly 164mm. With the completion of the general design, a parts-specific design process is used to calculate how the above numbers will be achieved at the component level. For example, various hydraulic, pneumatic, linkage, and gear based solutions were considered before deciding on the final design. The vehicle is designed using CAD software (Solid Works) and then tested and optimized using the built-in FEA package. The analysis of the model is done to assure that the components withstand an anticipated set of forces with a given safety factor. The suspension arms were designed to be both very compact when retracted, (Figure 4) and yet stable when

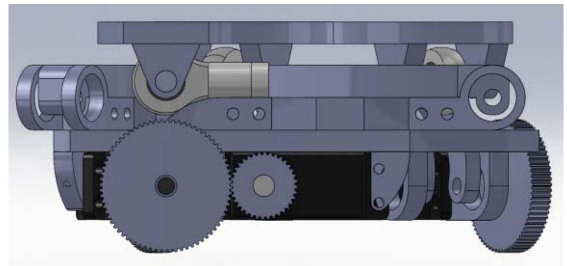

Fig. 4. Suspension arm in fully closed position.

extended, (Figure 5) all while minimizing the force required to change states. A modified Sarrus linkage was developed to accomplish this task. This mechanism differs from a traditional Sarrus mechanism in two regards. Firstly, these mechanisms traditionally use two or four parallel links to actuate and connect the two ends. This vehicle uses a three link system to optimize the throw of the mechanism in the constrained outer radius provided by the vehicle's wheel. Because of the geometry involved, a three link mechanism can extend 22.5% more than a four link system. Furthermore, Hitec HSR 5980SG servomotors were used because of their ease of integration and high performance. Geared down 2:1, the servo's specifications of 0.14 s/60^{o} and 30 Kg-cm of torque produce an effective transition time of 0.42 s with a force of 30.8 N on the wheel. The more innovative aspect of the mechanism is the ability to pivot the wheel in any direction, as opposed to conventional Sarrus mechanisms which maintain parallelism between the two adjacent planes. This is achieved through the use of ball joints, which are able to rotate up to 22^{o} in any direction according to how the three links are actuated by the servos. This means that parallelism can be maintained between the wheel and the ground, even if the suspension arm is rotated. This property can also be used to steer the vehicle, meaning a separate dedicated steering mechanism would not be necessary. Furthermore, this mechanism can be used to alleviate the stresses on the vehicle during telescoping by steering the wheel according to the direction of the combined velocity vector. The wheel must be telescoped at θ_T which can be found by:

$$\tan\theta_T = \frac{V_{expansion}}{V_{forward}}$$

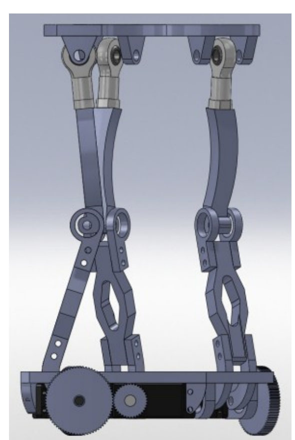

Fig. 5. Suspension arm in fully open position.

Where

$$V_{expansion} = \sin\,(\omega_{servo})\; R_{arm}$$

In these equations, $V_{expansion}$ is the rate at which the suspension arm telescopes, and $V_{forward}$ is the instantaneous forward velocity of the vehicle. R_{arm} is the effective radius of the actuating arm, and ω_{servo} is the rotational speed of the servomotor.

For construction, material selection was a very important aspect of the suspension arm design. 6061 Aluminum was chosen for the bulk of the suspension arm links because of its versatility in terms of both machinability and strength at the prototype's scale. Simulations were done using FEA and under expected loading, a safety factor of 1.58 was employed as can be seen in Figure 7. Rotational bearings were chosen (not included in the renderings) to minimize the friction throughout the range of motion of the links while also minimizing slack. Nitrile gaskets will be used for the tires as they will facilitate turning, while preventing the vehicle from sliding due to normal acceleration while cornering.

Besides the mechanical design and construction considerations, the control system for this vehicle will need various sensors to provide important information about the system. An optical or rotary encoder will be mounted to one of the wheels to determine the velocity of the vehicle at all times. Furthermore, the instantaneous radius of curvature of the vehicle will be calculated based on the positions of all of the servos in the suspension arms. Accelerometers and gyroscopes will be used to measure the perturbations felt by the vehicle either centrally or with one set at each corner. The next step in the procedure is to design and tune the PID system that will be used to control the length and position of the suspension arm. The physical system will be modeled in SIMULINK as accurately as possible. Control signals will be necessary for the lengths of the four suspension arms, as well for the angular positions.

Closed-loop analysis and testing will be the two final steps in the methodology of this project. Once the system is completely assembled, it will be driven over different kinds of rough terrain, and the reaction performance will be analyzed. The results can be compared to the various mathematical models as described above. Furthermore, by performing detailed studies of the system in different conditions, it will be possible to discover details and possibly even whole concepts that can be improved. These changes will be transformed into an extensive list of revisions, some of which may be performed, while the rest will be saved for future iterations of this project.

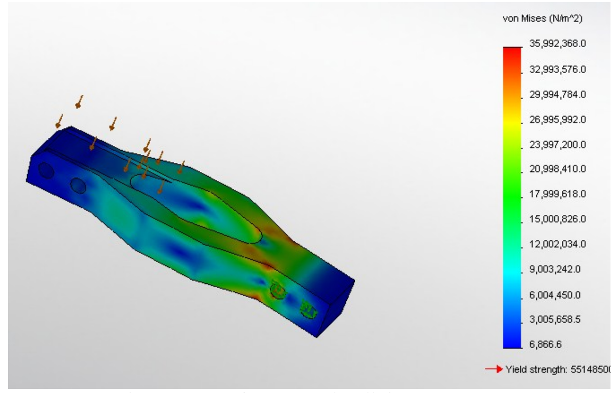

Fig. 7. FEA of a suspension link component.

IV. Preliminary Prototype results

At the time of submission of this paper, only some preliminary prototype results were obtained related to recent work of the first author. This work consisted of a solid, pivoting axle with a built-in accelerometer. When the wheels go over an obstacle, the accelerometer measures the tilt and converts the reading into an angle. This angle is then converted into a required amount of shock preload that will be necessary to compensate for the disturbance, and then servos turn cams which provide the necessary preload through a cantilevered link system. This enables the cab (or central portion) of the vehicle to remain flat (parallel to the ground) even if the axles change their angle when overcoming obstacles. This sequence of adjustments can best be demonstrated through the following clips taken from a video of the vehicle overcoming an obstacle (Figure 8). For clarity, the axis of the axle has been highlighted in green, and the cab in pink. The reaction of this system is a clear example of the above explanation of how active suspensions can be used to compensate for external noise. The work of this paper builds on this previous work of the first author by refining the design of the suspension and, especially by adding a control system with the potential for better performance.

V. Conclusions and future work

This paper presents an R&D project on a novel active suspension system that is capable of traversing both difficult terrain, and confined narrow spaces. By potentially being able to travel in the extremely difficult range of terrain in the Third World, this project can benefit the economic and

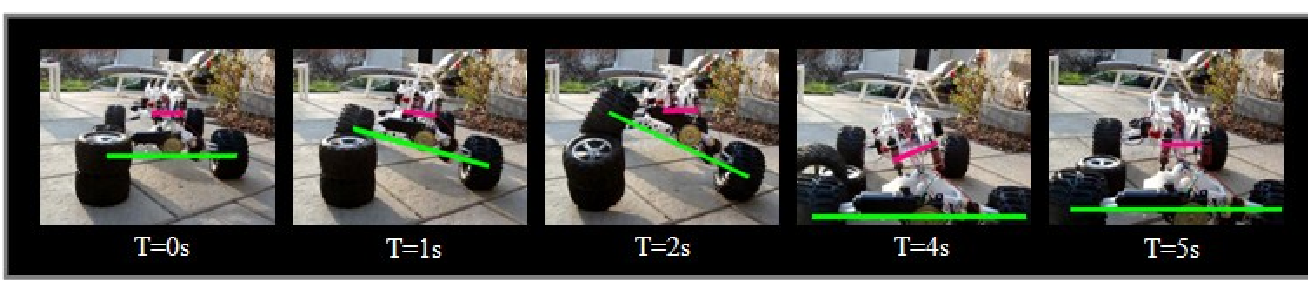

Fig. 8. Vehicle experiencing a disturbance and recovering.

social development of those societies. It is therefore a research project which moves from theoretical conceptualization to practical benefit for many potential future users around the world.

Future improvements to this platform include a much more thorough sensor array and the necessary filtering so that all of the additional data will be fused in an effective way. In addition to the included accelerometer/gyro, ultrasonic range finders will be used to predict how upcoming terrain will perturb the vehicle, allowing it to predict what compensation will be necessary, rather than simply reacting to previous sensor feedback. Integrating multiple sensors using Kalman filtering will also be considered to yield more accurate data fusion. Also, as mentioned earlier, experiments will be done with the implementation of different chassis shapes, thanks to the modular nature of the arms. One such interesting design could include the use of omnidirectional wheels mounted in an X shape with a minimal central chassis. This would not only increase the versatility of the vehicle, but also eliminate the current steering components. Such a configuration would showcase the extremely compact closed position. It would also allow to consider the interesting control issue of governing the omnidirectional wheel system when the suspension arms have different lengths.

REFERENCES

[1] K. Katsuyoshi, S. Oshita, A. Mine, Y. Hiwatashi, T. Konno, “Active suspension system of a vehicle” US Patent 5071159, Dec 10, 1991.

[2] R. Davis, P. Patil, “Electrically powered active suspension for a vehicle.” US Patent 5060959, Oct 29, 1991.

[3] M. Tabata, T. Hamada, “Active suspension of vehicle having system of compensation for cornering force.” US Patent 5294146, Mar 15, 1994.

[4] Hakam Kherallah, “Nissan’s Electric Future Unveiled in Tokyo,” *Shift* vol. 16, October - December 2009. [Online]. Available: http://nissan-me.com. [Accessed May 3, 2010].