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Actively articulated suspension for a four-wheeled vehicle

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Abstract

The purpose of the current work is to find a concept for an ATV sized unmanned vehicle which would easily overcome obstacles like steps and slopes. The work is written from a machine's designer's point of view. The following concept has been chosen for the vehicle: a four-wheeled vehicle with articulated suspension platform which is able to change its height, support polygon, as well its gravity centre in relation with the polygon. Hub motors are considered for a default design and an overview of some theoretical possibilities of the vehicle are given. Analogical vehicles which use similar articulated suspensions at least as prototypes are also briefly described. A general overview of their working principles has been brought out. The control of active suspensions and steering of vehicles are not discussed in the current paper.

Keywords: wheeled vehicles, kinematics of articulated suspension, building a prototype.

1 Introduction

The primary aim is that the vehicle must overcome steps and ditches which in height/depth are equal to the size of a wheel diameter. To provide the wheels with a broad range of options for suspension kinematics, the motors are installed in the wheels — in hub motors. The vehicle has a maximum speed of 5 km/h, thus the forces can be calculated on the static bases. As the weight of the vehicle is up to 300 kg, the payload to the wheel and the ground pressure are not considered problematic and the vehicle has a minimal number of wheels — four. The four-wheeled vehicle is simpler and cheaper than for example a six-wheeled vehicle. On the other hand, the four-wheeled vehicle has a greater probability for its wheels to fall into holes or ditches or getting stuck behind some obstacle. This applies especially on the occasion of a step for which the vehicle has to lift its gravity centre – the six-wheeled vehicle would be better in this case, because the lift of gravity centre for one wheel would be smaller. Even though the four-wheeler vehicle has been chosen for the current work.

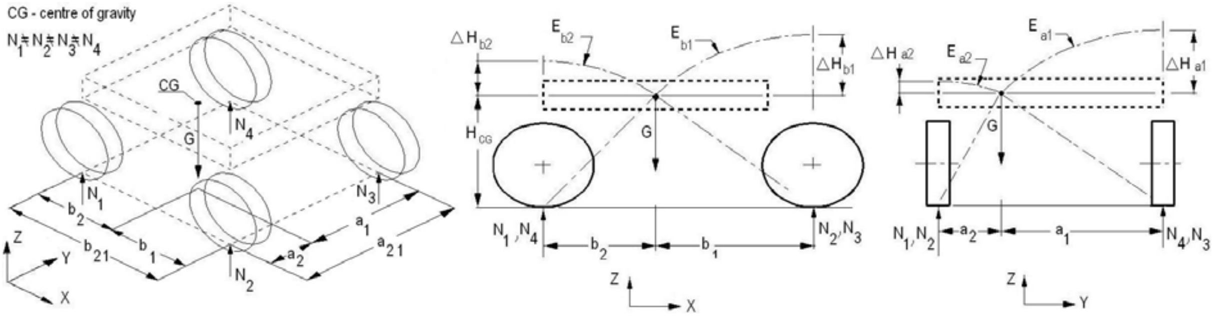


Figure 1. Gravity centre (G), normal force (N_x), support polygon (axb)

On Figure 1, some parameters of the four-wheeled vehicle are shown — location of the gravity centre according to the wheels, support polygon (a_{21} X b_{21}), height of the gravity centre's from ground, normal force N per wheel. Also is given the simplified trajectory of the gravity centre in case of the roll-over (curve E) and it is an evolvent profile. The distance ΔH_{xx} is the rise of the gravity centre during a roll over (around x or y axis). On the basis of ΔH_{xx} is possible to calculate the potential energy as a measurement for static stability.

While moving the four-wheeled vehicle on uneven terrain which has a passive suspension where the surface variation is at least half of the wheel's diameter there will be two problems. Firstly it is difficult to have contact with the ground or/and the normal forces will vary a lot. Secondly, the vehicle can lose its stability and roll over. To avoid these problems it is necessary to adapt the wheels on the ground and idealistically the vehicle should be horizontal during moving. It seems that to have good terrainability, all wheels should have equal normal forces which would make possible to load every wheel with equal traction force. As the gravity centre of the vehicle is not in the middle of the support polygon, only the horizontal position of the vehicle does not make normal forces equal for each wheel. Moreover, it is not always good to have equal normal force for each wheel considering the variation of the terrain parameters. When the wheel has been located behind a step or in a trench, the depth/height of which is equal to the wheel's diameter, the wheel cannot produce any traction force by rotating. Thus it would be better to release the wheel from normal force and lift it up over an obstacle. At the same time, adding payload to others wheels which are able to produce traction force for locomotion.

To implement the idea an extra movement is needed that would move a wheel(s) according to the gravity centre. It is possible to move the wheel(s) up-down or back-forth, but the movement can also be circular (Figure 2). In the last case, the usual suspension function and the movement of the gravity centre would be integrated in the same movement, depending on the rotation angle (α) and also on the direction of the rotation axis. In principle, the articulated vehicle could also have movement joints integrated with the body (D in Figure 2). In this case, the body of the vehicle is divided into sub-bodies, every wheel is attached to its sub-body, the sub-bodies are moving in accordance with each-other. Therefore, every wheel has a normal payload connected only to its sub-body. Such a concept can be used for bigger machines, where working aggregates can be separated and distributed.

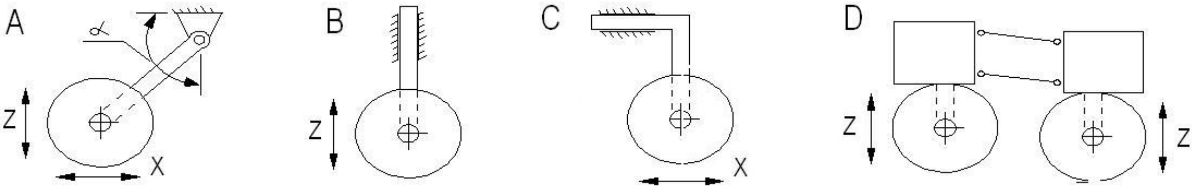
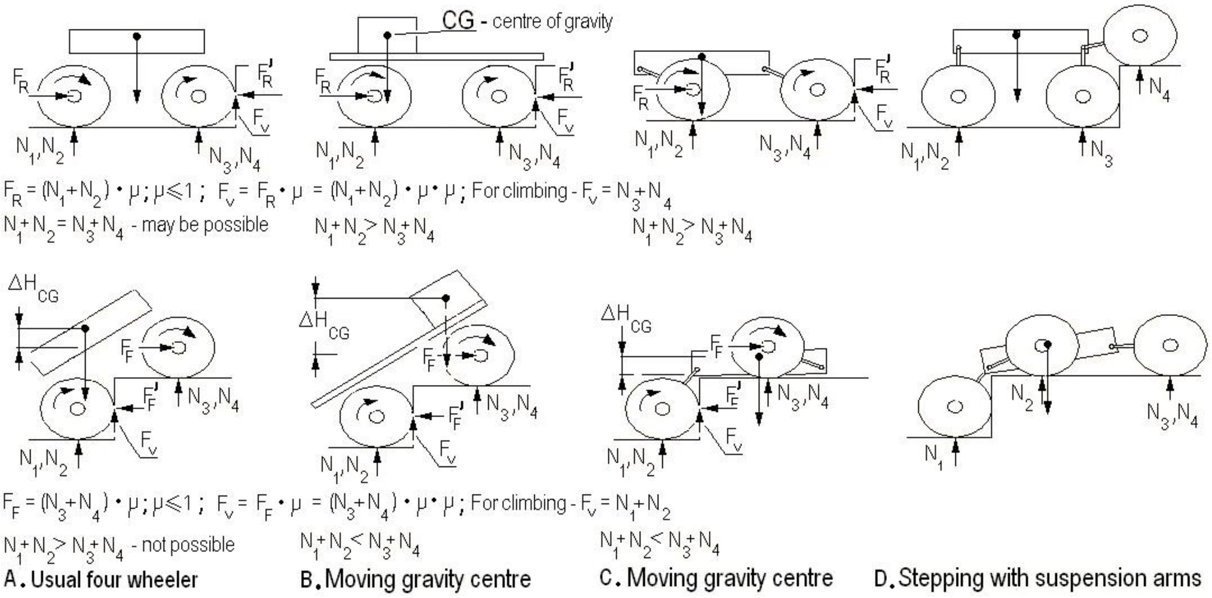


Figure 2. Rotating, translator (up-down), translator (back-forth), articulated body

The vehicle must climb a step that equals with the wheel diameter. Four different cases where a four-wheeled vehicle is trying to move over an obstacle are shown on Figure 3. The height of the gravity centre is randomly taken, but it is situated in the middle of the vehicle. On the upper row of Figure 3, the vehicle's front wheels are climbing over the step and on the lower row its rear wheels are climbing to the step. When considering the lift of the gravity centre, then in the case of step ideally every wheel must give an equal amount of force and energy to overcome the obstacle. But the wheel(s) that is pushing it-self against the vertical wall of the step cannot roll forth; instead the wheels must roll up together with its payload. Now the others wheels, by using the rest of the payload, must push/pull the wheel that is against the wall so strongly that this wheel could roll-climb up thanks to the friction between the vertical wall and the wheel (μ on the Figure 3). The climbing with the usual four-wheeled vehicle (A on the Figure 3) is statically not possible because it lacks pulling force for the friction of the rear wheels. On the two middle versions (B and C), there is an auxiliary movement that does the work for lifting the gravity centre higher and unloads the wheels which are fronting against the vertical wall. On version B the movement is linear and the clearance of the vehicle is not changed. On version C, the clearance is also lowered. On the last variant D, the wheels are lifted to the step one by one and an auxiliary movement exists that lifts the gravity centre as well. However, in the case of the four-wheeled vehicle it is probable that when one of the wheels is lifted up, the gravity centre may not be in the triangle between the rest of the wheels and the vehicle will start to roll over. To avoid that, it is necessary to have a moving gravity centre function or to change the support polygon. The situation is better in the case of the six-wheeled vehicle, because when one wheel is lifted, the static stability is still guaranteed. Anyway such a locomotion technique is also rather complicated.



A. Usual four wheeler B. Moving gravity centre C. Moving gravity centre D. Stepping with suspension arms

Figure 3. Going over a step with a four-wheeled vehicle

Thus an active gravity centre movement in longitudinal direction is needed. Whether an active suspension (varying clearance) is also needed, remains firstly an open question. On the other hand, by using kinematics of the suspension arm (A, on the Figure 2), the changing of the location of the gravity centre in longitudinal direction and the suspension are originally inborn. Actually, the suspension could be also passive or semi-active. While an active suspension can give and take energy from total locomotion energy, the semi-active suspension can only absorb the energy from the total system [5]. In case of the semi-active suspension it is possible to control the resistance of the suspension on the up-down movement, but the movement itself is reached because of the traction force of the wheels and the normal force. The passive suspension is a classical suspension, the resistance of which for normal force is always determined by the same characteristic.

2 Solutions that exist on the market or as prototypes

2.1 Forest machines — Harvesters

A harvester named Skogsjan was built in the beginning of the 80s. It is a four-wheeled vehicle with four suspension arms; each suspension arm had 1 degree of freedom (dof) + rotary movement of the wheel. The machine steered itself by a pivot link in the middle of the machine frame — frame articulated steering. That machine could change its clearance and balance itself, thus it can set up maximum counter mass during the harvesting process. Today, tree harvesters exist on the market, having balancing function. The harvester Ecolog is like the old SkogsJan, also the small harvester RCM has the same kind of kinematics. The harvester named MenziMuck has different kinematics. This machine can work on very high slopes (up to 40 %) and its every suspension arm has 3 dof + the wheel rotation. It steers itself by steering the wheels and also it can steer its suspension arms. With suspension arms it can also change its width and height. All these machines are driven by hydraulics.

Figure 4. Harvesters EcoLog [16], MenziMuck [15] and RCM Harvester [24]

2.2 GoDevil-DoLiner

There is not much information about this machine, but it is very good for an example. It is a car-boat — amphibious car. It can travel on land and also in water. It has frame articulated steering and the suspension arms rotate at least 360 degrees. Thus, it can easily change its support polygon and gravity centre. Probably in water, the suspension arms are lifted up.

Figure 5. GoDevil-DoLiner [25]

2.3 Six-wheeled military robot platforms Spinner, Crusher, Mule and Gladiators

Although the next vehicles are not four-wheeled vehicles, they are good examples. The first vehicle, called Spinner, is developed as a crash survival unmanned vehicle by Carnegie Mellon University at National Robotics Centre [1]. It is a six-wheeled vehicle and it can move its suspension arms up-down (1 dof), having a suspension travel of 18 inches. The suspension is based on hydra-gas [12]. The Spinner can survive a roll-over and continue its mission on the upside-down mode. The weight of the Spinner is over 6 tons, it is energised with electric in-hub motors and it uses skid-steering. The new version of the Spinner got named Crusher. This machine has 29% smaller mass than its predecessor and the travel of the suspension arms is longer. It can climb a step of 1.2 m and also a ditch of 2.1 m. The maximum slope in the moving direction is 30% and the maximum speed is 40 km/h.

Figure 6. Spinner and Crusher [1, 2]

MULE (Multifunctional Utility/Logistics and Equipment Vehicle) is a six-wheeled unmanned vehicle with an approximate weight of 2.5-ton (Figure 7). It has six independently articulating suspension arms (1 dof), which have rotary magnetorheological dampers for precise damping and adaption to a variety of terrains [13]. It is energized with in-hub electric motors and for steering it uses skid-steering. Its suspension-arms can rotate over 210 degrees and the vehicle can climb a step of 1.0 meters and also a ditch of 1.0 meters, while varying payload weights and the centre of gravity location. Also it can traverse side slopes greater than 40 %. This vehicle gave a lot of inspiration for the current work and for the prototype (Figure 14).

Figure 7. An earlier prototype of MULE (from MillenWorks) crawling the step [14]

On Figure 8, two six-wheeled robots named Gladiators are given; both vehicles have individually articulated suspensions (1 dof), are skid-steered and they do not use in-hub motors. The Gladiator on the left is developed by Carnegie Mellon University [26, 27] and BAE Systems. The suspension is developed by the same company as Crusher and Spinner [12]. The Gladiator on the right side is developed by Millenworks [14]. Also, this vehicle uses individual suspension but the rotation of suspension arms is not parallel with the axis of the wheels. The top speed of the Gladiators is 40 km/h.

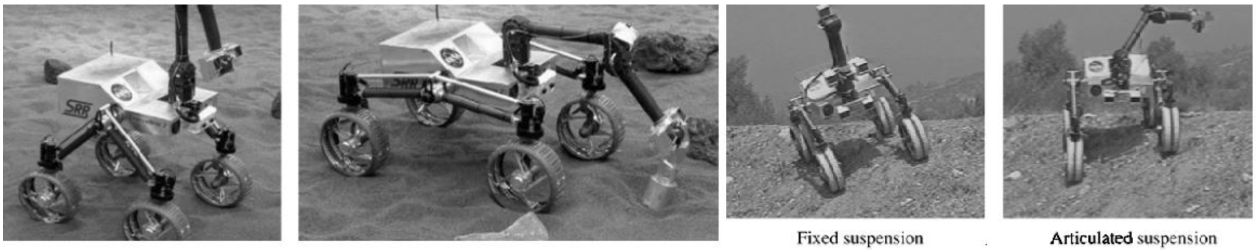
Figure 8. Gladiators, Carnegie Mellon University (left) [26-27] and Millenwoks [14]

2.4 Planetary vehicles

On Picture 9, a small planetary robot (6 kg) is given; it is a four-wheeled concept vehicle that employs an inverted-pendulum control algorithm [3]. This vehicle has 6 inner dof and it controls its gravity centre during driving, but it is not actively suspended, only three wheels are attached to the ground. This rover is skid-steered. JPL (Jet Propulsion Laboratory) did not develop this concept further and started to work with the six-wheeled rocker-bogie concept that does not use an active suspension at all. Two machines employing the rocker bogie concept are currently on Mars (on the middle-right on Figure 9). Here, it has to be considered that all successful planetary rovers until today have had passive suspension, not active, because of complications and possible low reliability of active suspension.

Figure 9. GoFor, second from the right, the RockerBogie family [17] and Scarab [20]

On Figure 10, the sample return rover (SRR) from JPL is given [8]. It has a four- wheel drive and steering. Also it has a passive rocker-type suspension system and independently controllable shoulder joints. In some limits it can also reposition its centre of mass by repositioning its manipulator. The rover weighs 7 kg and it is energized with electricity. The main speed of the vehicle is approximately only 6 cm/sec. A robot platform using similar locomotion kinematics is developed for drilling ground on the Moon [20], called Scarab (on the right on the Figure 9). But it is much bigger (300 kg) and it does use skid-steering.


Fixed suspension

Articulated suspension

Figure 10. SRR—Sample Return Rover [8]

2.5 Some robot platforms as prototypes

On Figure 11, four robots are shown. The robot on the left is called Hylos [9]. It is a small, 12 kg vehicle and it has four legs and wheels. The second robot from the left is called WorkPartner [6] and it is a bit bigger vehicle with a mass of 300 kg. Both these robots have similar 2 dof suspension mechanisms for each leg and they use linear electric actuators. These can balance and change their support polygon separately. Also, both these robots can use different locomotion modes, they can just roll or also rolk — locomotion that is something between walking and rolling. Hylos steers its every wheel separately, having totally 16 inside dof. WorkPartner in the middle has an active 2 dof body-joint that is used for steering. The second robot from the right (Figure 11) is a car-sized robot called Ant. Its kinematics is similar to forest harvesters, every rotating suspension arm has 1 dof and in the middle of the vehicle there is a pivot link for steering, the vehicle is energized by hydraulics. The robot from the right (Figure 11) is a six-wheeled robot called Jarvis. Jarvis is an interesting example because it uses translator movement for compensating terrain unevenness (not rotary). All these robots use in-hub electric motors and electricity as the medium; except for Ant.

Figure 11. From the right, Hylos [18], WorkPartner[6], ANT[22] and Jarvis [4]

2.6 Conclusion — possible functions when using actively articulated suspension

In most of the examples, the articulation of the wheel is implemented with one movement (except the robots Hylos and WorkPartner) and this is rotary movement (except Jarvis). At the same time, the axis of the rotary movement is parallel with the movement of the wheel (except the Gladiator from MillenWorks and MenziMuck). In that case, the wheelbase of the vehicle is always the same (a_1 and a_2 on Figure 1), but the distance from the gravity centre to the wheel is changing (b_1 and b_2 on Figure 1). This also depends on the travel angle of the suspension arm (α on the Figure 2). Most of the vehicles have motors in the wheels (except Gladiators) and the energy is translated to the wheel by electricity or hydraulics. This kind of a system makes it possible to steer the vehicle without a differential and gives big freedom for different movements of the wheel, only the cables/hoses will limit this. A minus of the in-hub motor is that it makes the wheel heavier and adds inertia to the system. But as the vehicles move rather slowly, it is not a problem. It is rather an advantages because it makes the gravity centre lower (H_{CG} — Figure 1) and this is very important on the uneven terrain.

What are the extra advantages beside the main suspension function (compensate terrain unevenness) in having some kind of active articulated suspension:

a- balancing and changing the clearance of the vehicle. Mainly used by machines that have to keep themselves strictly horizontal on an uneven terrain, for examples harvesters and some lifters/trailers (Mammoet trailers [18])

b- possibility to change the gravity centre according to the support polygon. It makes it possible to load/unload wheels — vary payload.

c- option to change the support polygon without changing the payload of wheels. This is useful while steering the vehicle, especially if the vehicle is skid-steered.

d- if the suspension has really long travelling distance and there are no aggregates on the top of the vehicle, it is possible to move with the vehicle in the upside-down mode.

e- if the articulation enables to move the wheel in locomotion direction, then it is possible to use it for locomotion. If the suspension arms are endlessly rotating, it is possible to use crawling locomotion with locked wheels. This crawling is similar to the locomotion of extremely big draglines, up to 1000 tons with a speed of 0,2 km/h [21]). In this case, the machine "walks" using rotary moving legs and in the meanwhile, it lets it-self on its bottom. The robot Chaos [23] is using similar kind of locomotion. The problem is of course that such kinematics takes a lot of room. If the suspension arms do not rotate endlessly it is still possible to use them for locomotion. It is called rolking (WorkPartner and Hylos), moving suspension arms back and forth and blocking the wheels respectively. In soft soil a locked wheel is harder to pull when this wheel is capable of pulling itself – in the case it is under the same payload [6].

3 Creating the prototype

The UGV (Figure 14) is developed by Tallinn University of Technology [10]. By building the prototype, a principle that it must be fast and easily practicable has to be considered — only purchasable products are used. The vehicle is energized with electricity and has batteries on it. The in-hub electric motors are used.

The next question is the kinematics of the additional movement of the wheel. Here, rotary movement is chosen, it does not need any complicated bearings like the translator movement does. The axis of the suspension arm is parallel to the axis of the wheel. In this case, the gravity centre could be moved according to the support polygon and also the height of the vehicle can easily be changed. As the support polygon can be changed to a minimum, skid-steering will be used. There will be no additional dof for steering and only 1 dof per each suspension arm + rotation of the wheel. The in-hub motor will be mounted directly on the suspension arm.

A disadvantage of the rotary suspension arm is the problem that in a certain terrain, a choice has to made whether the platform has to be kept horisontal or the support polygon has to be maximised. This is because in some cases, the wheels move too near to the gravity centre of the vehicle (on the left on the Figure 12).

The suspension arm can have different travelling ranges (α on the Figure 2):

1- By using a linear actuator it is possible to reach a rotating degree up to 160 degrees, but to lower the vehicle to the bottom and at the same time to extend the suspension arm straight forth, at least 180 degrees (plus some 20 degrees) is needed.

2- Endless rotating is difficult because the information and energy contacts are needed to allow the rotation of the wheel. On the other hand, it is possible that the suspension arm can rotate a number of times having the full 360 degrees rotation — as long as cables can be twisted.

3- It seems that is pointless to have a rotation of 355 degrees, because the suspension arm cannot do a full circle and it is not possible to bring the wheel fully down in both directions (clockwise and counter clockwise).

As it is a prototype and it should have as many option as possible, then the second variant is chosen — n X 360 degree, where n is at least 3. This variant allows testing many locomotion modes, also the crawling and rolking in the case of a flat surface.

In the ideal case, the transmission gear of the suspension arm should have some kind of suspension characteristics — elasticity and it could work in a semi-active mode. For example, hydro gas suspensions or magnetorheological suspensions. But they are not easily reachable machine elements. Anyway, one of the cheapest option is chosen — worm gear. If the suspension function is necessary, suspension arms with an extra dof must be designed. This extra dof will be accommodated with a passive or semi-active suspension-shock absorber. This variant would be useful in moving with higher speeds, but as the vehicle moves only up to 5 km/h, the question is at the moment not topical. Actually, the suspension could be implemented also by software in the regulator, but it would be too complicated, at least for a prototype. Thus, this vehicle has 8 internal dof and it is possible to test the rolling, rolking and crawling modes.

Next, the length of the suspension arm is chosen. The distance between the rotating centres of the suspension arms is given with the dimensions of the vehicle and also the diameter of the wheel is given. These parameters determine how much it is possible to move the gravity centre according to the support polygon and vary the payload for each wheel. The length is chosen according to the possibility to vary the payload from 10% to 40% of the total mass of the vehicle, this is for one wheel. The longer the suspension arm, the bigger the load variation, but on the other hand, the greater length increases the load for the transmission gear of the suspension arm. Here, it can be noticed that the final prototype of the six-wheeled vehicle MULE has same size suspension arm length as the wheel radius. If the suspension arms do not rotate 360 degrees, there is an additional constraint for the length of the suspension arms and the distance between rotating centres of the suspension arms. If going over the step obstacle and using the payload variation (C on the Figure 3), the front wheels on the step must be pulled back near to the gravity centre. But this is not possible, if the suspension arms are too long. The vehicle may roll over.

If climbing a slope longitudinally, there are two variants. In the first variant, the vehicle is kept horizontally and the back wheels are located near the gravity centre. In the other variant, the vehicle is parallel to the slope and the wheels are located towards the furthest point from the gravity centre (in this case steering is complicated). As it can be seen from the picture, the stability is much better in the case of the second variant ($\Delta H_B < \Delta H_S$), also as the back wheel is not so near to the gravity centre, the traction moment of the wheel does not influence the stability so much.

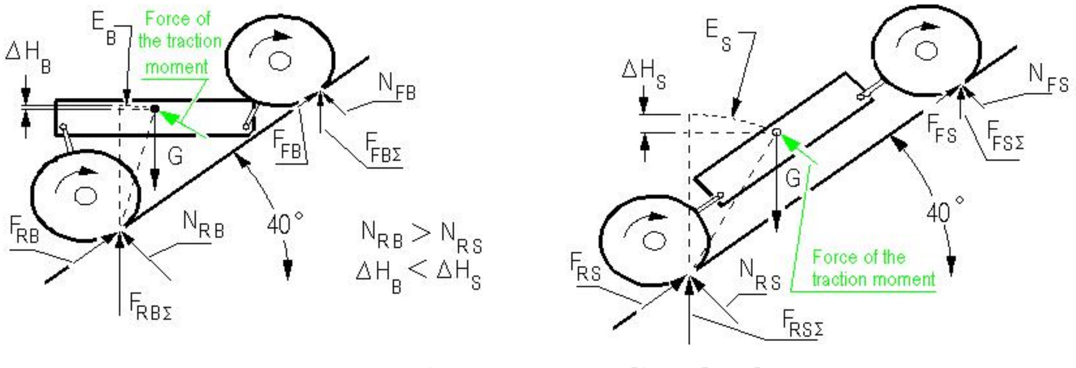


Figure 12. Grawling the slope

Travelling on a side slope is rare since it is always better to travel in longitude with the slope, when possible. But theoretically the vehicle must be able to keep itself horizontal on a 30-degree side slope. This depends on the length of the suspension arms and the width of the vehicle.

While passing over a ditch, it is also possible to use the movement of the suspension arms. A usual four-wheeled vehicle can climb a ditch that has a width of 0.85 of its wheel diameter. If varying the payload with articulation of suspension arms and rolling on tree wheels, the width of the ditch can be much longer than in the case of usual four wheeled vehicle. On the Figure 13 is given a row of pictures where the vehicle is passing over a ditch and articulating with suspension arms. From the picture is possible to estimate roughly that the width of the ditch can be 1.3 times the wheel radius pluss the radius of the suspension arms. This is of course a simplified case and in 2D where the angle around x axis (Figure 1) is always zero.

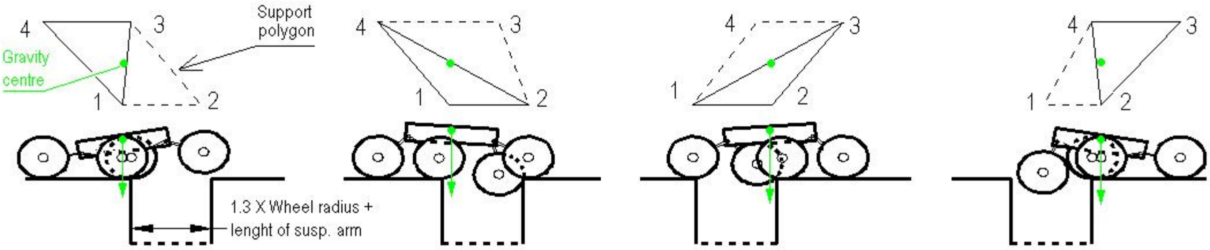


Figure 13. Going over a ditch

4 Conclusion

As this vehicle is unmanned, it will be remote-controlled or execute some operation anonymously. In both cases, there is not enough information about the situation of the terrain in comparison with the case when a human drives a vehicle. The simplest locomotion mode that will be tested firstly is usual rolling, but most of the vehicle mass will be distributed to the rear wheels and the first wheels will be situated in front of the vehicle. So is possible to “feel” the terrain and it is rather simple to turn the vehicle as most of the mass is on the rear wheels. Such locomotion is similar to Go-For. If the first wheels will fall into a deep trench, then it is possible to pull them back, because most of the vehicle mass is still on the rear wheels. When using the balancing function, then firstly only the side slope will be compensated.

The next development work is to create a mathematical model and to build the regulator. Today, this prototype cannot feel the force in its suspension arms. Thus, simplest is to test balancing on the flat surface. In this case, if knowing the roll and pitch angle and giving the height of the vehicle, it is possible to press all the wheels equally onto the ground.

From the concept point of view it would be interesting to figure out what can be the terrainability of a vehicle that has suspension arms only on one end. On the other end, there could be a usual suspension from ATV. It gives much better options for steering the vehicle. Also, it is necessary to work with the question if it is possible to move the suspension arm with a linear driver like a ball screw or some kind of a hydraulic cylinder.

Figure 14. Prototype in an early stage [10]

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