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Mars Rover Mechanisms Designed for Rocky IV

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ABSTRACT

A Mars rover prototype vehicle named Rocky IV was designed and built at the Jet Propulsion Laboratory during the fall of 1991 and spring 1992. This vehicle is the fourth in a series of rovers designed to test vehicle mobility and navigation software. Rocky IV was the first attempt to design a vehicle with "flight like" mass and functionality. It was consequently necessary to develop highly efficient mechanisms and structures to meet the vehicles very tight mass limit of 3 Kg for the entire mobility system (7 Kg for the full system). This paper will discuss the key mechanisms developed for the rover's innovative drive and suspension system. These are the wheel drive and strut assembly, the rocker-bogie suspension mechanism and the differential pivot. The end-to-end design, analysis, fabrication and testing of these components will also be discussed as will their performance during field testing. The lessons learned from Rocky IV are already proving invaluable for the design of Rocky VI. Rocky VI is currently being designed to fly on NASA's MESUR mission to Mars scheduled to launch in 1996.

INTRODUCTION

Research on planetary rovers began in the early sixties for the Surveyor lunar rover (which never flew) by M.G. Bekker [1]. Bekker's work culminated in a six wheeled rover with a flexible body. Planetary rover work lapsed for many years until the Mars Rover Sample Return mission was conceived. At that time the Jet Propulsion Laboratory (JPL) began investigating new rover configurations to offer even higher mobility. The design evolution began with the invention of six wheeled configurations utilizing links to articulate the body so that equal weight distribution was maintained on all wheels at all times. This rover was

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named the Pantograph. A Rocker-Bogie configuration was then developed to overcome some of the limitations of the link articulated rovers. Rocky and Rocky III were built to prove their rock climbing capability. Rocky III, a rover weighing 25 kg and 60 cm long showed enough potential as an integrated rover system that Rocky IV was funded by NASA's code-R to demonstrate a full end-to-end behavior controlled high mobility planetary rover system. The project was managed in a fast paced "skunk works" fashion to show that such a vehicle could not only be built, but that it could be done quickly and inexpensively. In addition to the functional requirements of the rover system it was required that the rover be built to "flight-like" mass of only 7 kg. Some of the key components of the rover mobility system will be discussed in more detail.

SUSPENSION

The term Rocker-Bogie refers to the two link suspension system comprised of a trailing rocker arm with one wheel, and a bogie with two wheels pivoted at one end of the rocker arm. This configuration gives the vehicle excellent terrain following abilities which is crucial for a high mobility vehicle. The suspension geometry, which includes wheel diameter and spacing, pivot locations and center of gravity location, was optimized in 2-D for the minimum coefficient of friction required to climb axle high vertical bumps when the vehicle was going both forward and backward. The 3-D performance on rocky terrain was then analyzed using an elastodynamic analysis software package called Adams [2].

Figure 1 shows the geometry of the Rocky IV suspension system. The front and rear wheels are steerable whereas the center wheels are not. This allows Rocky IV to turn in place by steering about its center point. The behavior control navigation scheme relies on sensor information on the rover suspension to tell it what the rover is doing and what position it is in. This allows the computer to decide if the rover is getting into a hazardous situation or not. To provide this information potentiometers are used to give the angular position of the bogie with respect to the rocker arm. Physical stops limit the maximum rotation but the sensors allow the rover to stop and back away before these limits are reached. A potentiometer is also located in the differential link, which will be discussed later, to provide the rest of the information required to define the state of the rover. The two physical stops are called the bump stop and the cable stop. The bump stop consists of two rubber pads attached to a steel pin through the back of the bogie, which makes contact with the back side of the rocker arm's forks This limits foreword rotation of the bogie. The cable stop is a cable attached to the aft end of the bogie going up the the rocker arm through a small hole. Impact shock is mitigated by compressing a foam pad between the rocker arm and the cable end as the cable reaches maximum extension.

The maximum rotation of the bogies with respect to the rocker was chosen by considering the rover's ability to traverse a trench. Figure 2 shows the rover configuration analyzed. If the front wheel is allowed to fall too far, the moment created when contacting the far side of the trench would have a tendency to overturn the vehicle. If the front wheel was not allowed to rotate enough the vehicle's terrain following ability would have been reduced. The angle was chosen which required the front wheel to have the same minimum coefficient of friction to climb the far wall as the largest minimum coefficient of friction required for any one of the wheels to climb a step directly in front of it. This angle is 30 degrees.

A static test model of the main rocker arm structure was fabricated early on to verify the structural analysis done on it. A series of dead weight static tests were conducted where the maximum deflection was recorded. The tests were performed by incrementally adding and then removing weights suspended from the rocker arm. No more weight was added when there was 2% yield on the structure. The results verified the analysis to within 10 percent of the predicted performance. The results of the tests were that the servo mounting structure was thinned down and some thickness was added to the top of the arm just above the main pivot.

WHEEL DRIVE ASSEMBLY

The wheel drive assembly is comprised of two major parts, the wheel strut and the motor-gearbox. The wheel strut is the structure which holds the wheel to the suspension. Steering is done on four of the six struts at the top of the strut. Due to the fact that there were six wheel drive assemblies, it was crucial that as much mass as possible be removed from the structure without compromising its integrity. The first attempt at the strut design involved machining a channel down the length of the strut and then closing the cross section by welding on a cover. A complete test strut was fabricated in this manor early on. The machine time and the added wall thickness' required to counter the effect of annealing caused by welding, proved to be costly and heavy. With the knowledge gained from having fabricated the first test model we were able to invent a lighter and cheaper strut. This approach involved designing a tool to allow under cutting in the strut cross section. The process utilized an end mill with a neck whose diameter was half that of the cutting diameter. The tool first penetrated all the way through the strut, it was then raised so that the cutting length of the tool was in the middle of the strut cross section, thus leaving a predetermined wall thickness above and below the tool. The part was then moved around under the tool (N/C machine) so that a region larger than the through hole was milled out, in effect hollowing out the strut. Figure 3 shows the resultant wavy pattern in the strut walls. The machining for the strut was done on a numerical control end mill in order to save both time and money.

A NASTRAN analysis was done on the strut using the worst case loading conditions. The worst case loading was assumed to be an accidental drop of one wheel diameter. Figure 4 shows the NASTRAN model of the strut. The maximum stress was found to be on the inner portion (of the arc) of the 3rd and 5th through holes (from the top) as well as the outside portion of the 4th through hole. There was not enough time in the project to optimize the strut design so the NASTRAN analysis was used only to verify that the structure was not stressed beyond its limits. The analysis did give a considerable amount of insight as to where mass could be removed and were mass should be added. This information is already proving useful in planing the follow-on rover strut design.

Steering is performed on four of the six wheels. A single thin-line X-type bearing is used to allow rotation. The bearing is protected from dust by two O-rings, one above and one below it. In an effort to save time and money, commercial radio controlled model sailboat servo motors are used to perform the steering. One servo per steerable wheel is used. The servos are hard wired into the computer which controls their rotation. Ackerman steering is employed for Rocky for efficient turning. Rather than compute all the angles required for all wheels for any given turn angle, six discrete turn angles were preprogramed and the ackerman angles were "looked up" to make a turn.

The drive mechanism contains a single 12 volt DC permanent magnet electric motor coupled to a four stage planetary gearbox. The motors were purchased from Escap but the gearbox was purchased from a surplus store and modified to reduce the mass of the casing. The gearing ratio is 400:1 and provides a maximum of 0.20 N cm of torque. This torque level ensures that Rocky 4 is not torque limited under the worst predicted loading conditions. The motor rotations are counted for the computer via an optical encoder mounted just before the pinion on the motor drive shaft. An encoder wheel, painted half black and half white alternately reflects light back to the encoder once per revolution. Four hundred revolutions indicated one wheel revolution. The last stage of the gearbox couples directly to the wheel hub through four steel pins, one per planet gear. The wheel hub was also machined with a numerical controlled milling machine. Figure 5 shows a photograph of a complete bogie assembly with all the parts of one wheel drive assembly displayed. The wires are for the optical encoder, no motor wires are shown.

DIFFERENTIAL PIVOT

Rocky 4 is a single body design with independent left and right suspension. The main structural support to the body is via a single aluminum tube connecting the left and right side. This alone however leaves one degree of freedom unconstrained, pitch rotation. This degree of freedom is taken out by a differential pivot which mounts at the rear of the rover body and connects the left and right suspension. The pivot has the effect of averaging the motion of the left and the right, thus providing a relatively smooth and stable ride for onboard electronics. The pivot mechanism is made up of a main mast with a pivot at the top. The angle of the pivot axis of rotation is parallel to the line connecting the rocker arm main pivot and the link attach point. A cross arm pivots about this axis and extends from the left to the right suspension. The cross bar is connected to the suspension via two links with ball joint ends. The ball joint ends allow the links to rotate and follow the rocker arm and the cross bar freely. The height of the mast was determined by the maximum angle the ball links could rotate laterally. To save time and money model airplane ball links purchased from a local hobby shop were used, and performed very well.

As was previously mentioned the differential link was encoded using a potentiometer to provide the computer with "attitude" information. The potentiometer was designed into the pivot design from the beginning to allow easy access for calibration and removal.

VEHICLE SYSTEM DESIGN

The total vehicle mass came out to 7.1 kg which was distributed as follows:

Control Electronics	1212 g
Rock Chipper	150 g
Video transmitter	500 g
Electrical systems	1717 g
Mobility System (structure)	3521 g

Rocky IV was designed and sponsored for a demonstration which occurred in early may at JPL in a dry riverbed behind the lab.. The Rocky IV complete system included the rover, a "lander" which provided a radio link to the rover, stereo imaging, an optical homing beacon and a radio link to the control crew. The purpose of the demonstration was to show an end-to-end operation of the high mobility behavior controlled rover system. To this end the demo required the rover to first exit the lander and deploy a functional micro seismometer one meter from the lander. A soil sample was then taken by Rocky with an onboard scooping mechanism. A rock to be inspected was then selected by the ground crew via the lander imaging system. The rover drove to the rock, avoiding hazardous obstacles on the way, took a spectrum of the weathered rock, chipped the weathering rind off the rock and took another spectrum of the virgin rock. The rover then returned to the lander on its own and deposited the previously acquired sample. A considerable amount of time was spent debugging and refining the software responsible for controlling the vehicle. The final result was a highly successful demonstration of the fully functioning system. Figure 6 shows the computer drawings used to fabricate piece parts as well as to configure the rover. Figure 7 is a photograph taken of Rocky IV just after final assembly.

CONCLUSIONS

The experiences gained from the end-to-end design and fabrication of Rocky 4 are already proving to be of great value. We are currently designing Rocky 6 which is scheduled to be launch aboard NASA's MESUR Pathfinder Mars lander in 1996. Many of the issues the design team must address have already been dealt with on a first order basis therefore allowing us to design a much better system. Some of the lessons learned are given here.

The field test verification of the quasi static computer modeling and optimization was tremendously valuable. It gives the rover design team a very high level of confidence in the design tools which have been developed over years. This level of confidence is very important for making accurate predictions for highly constrained missions such as MESUR which can not afford to carry large rovers to Mars. The field testing also revealed aspects of the design which are not feasible for modeling on a computer. Vehicle-ground interaction over rough and rocky terrain is the most important aspect. Field testing has shown when and where the rover would "hang up" on obstacles. It showed us that almost every time the rover became caught on a rock, it was able to successfully back out of the situation. It was also found that the wheel struts would occasionally catch on rocks and hold the rover back. Such testing is not only valuable for design purposes but will also prove valuable to operations planning.

Integration of the potentiometers into the vehicle structure was not as simple a matter as thought. Simplicity was a design goal in order to increase reliability. Unfortunately the simplest ideas were not always the lightest. Often the most mass efficient ideas were impossible to assemble. The final designs for the potentiometer integration was both simple and light, but was somewhat delicate at first. The potentiometers slipped during the first week of field testing. Fortunately only a simple modification was required to fix the problem.

Finally, the fast paced, low cost approach to the design was very successful. So successful that the JPL micro-rover project was singled out in the latest NASA report card as a successful example of cheaper, faster, better, and a paradigm for future projects.

ACKNOWLEDGEMENTS

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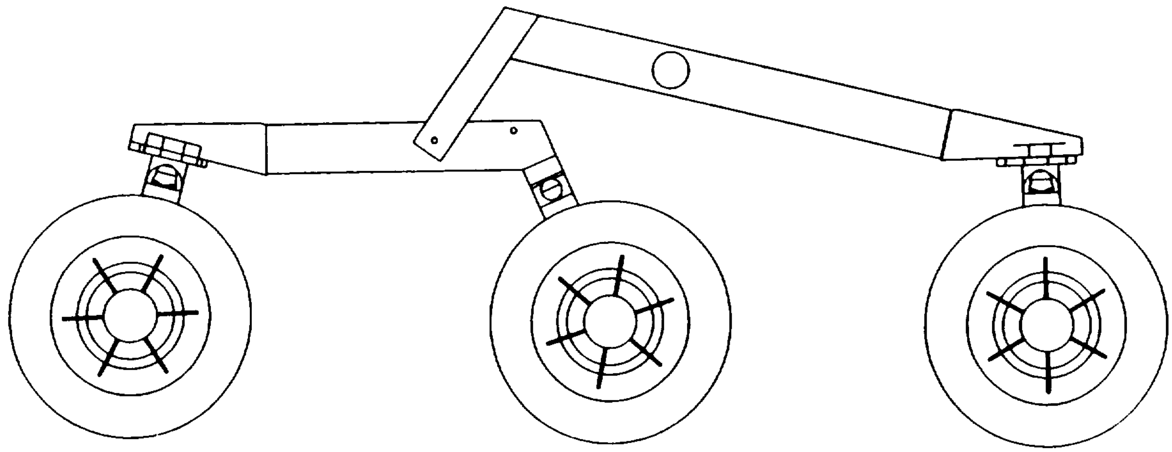

Figure 1. Rocky IV Rocker-Bogie suspension geometry.

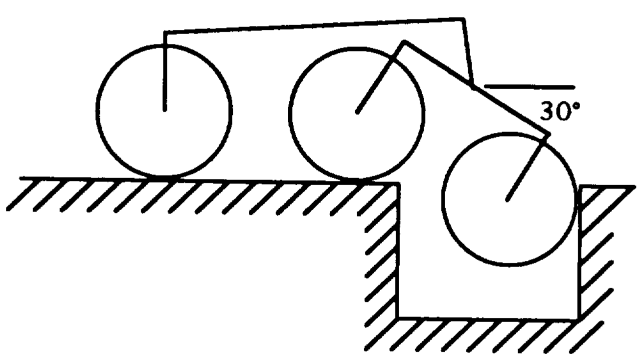

Figure 2. Geometry analyzed for the rover crossing a trench.

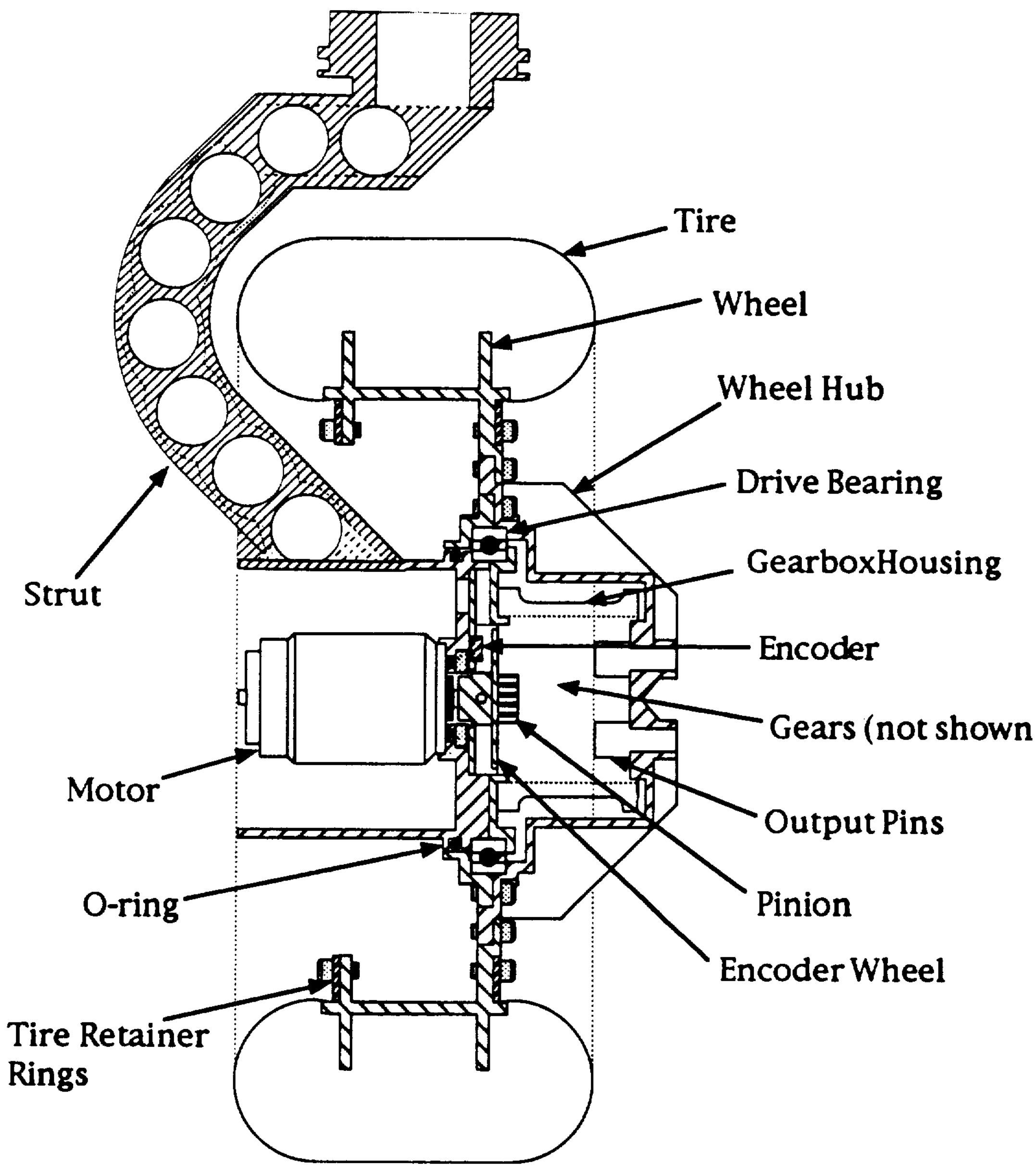

Figure 3. Wheel strut and drive assembly.

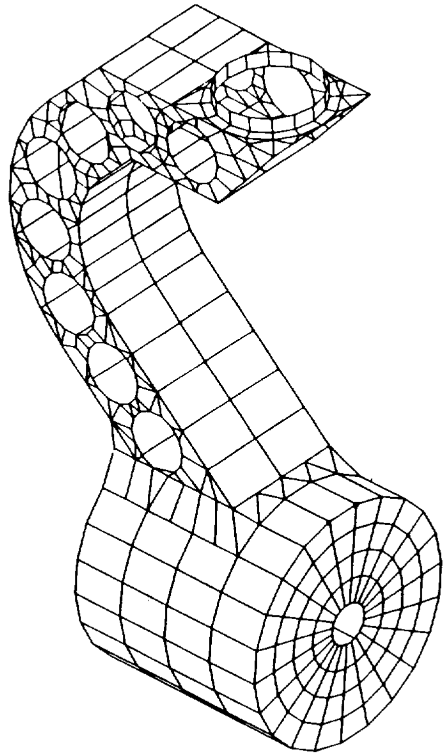

Figure 4. NASTRAN model of the wheel strut.

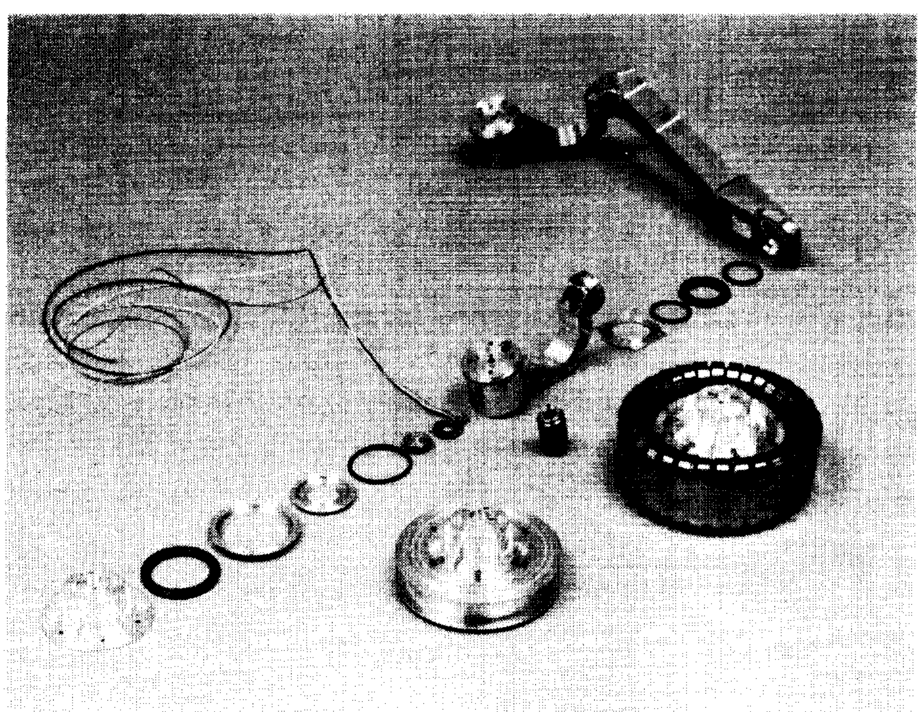

Figure 5. Photograph of the bogie assembly showing all of the parts for one wheel drive mechanism.

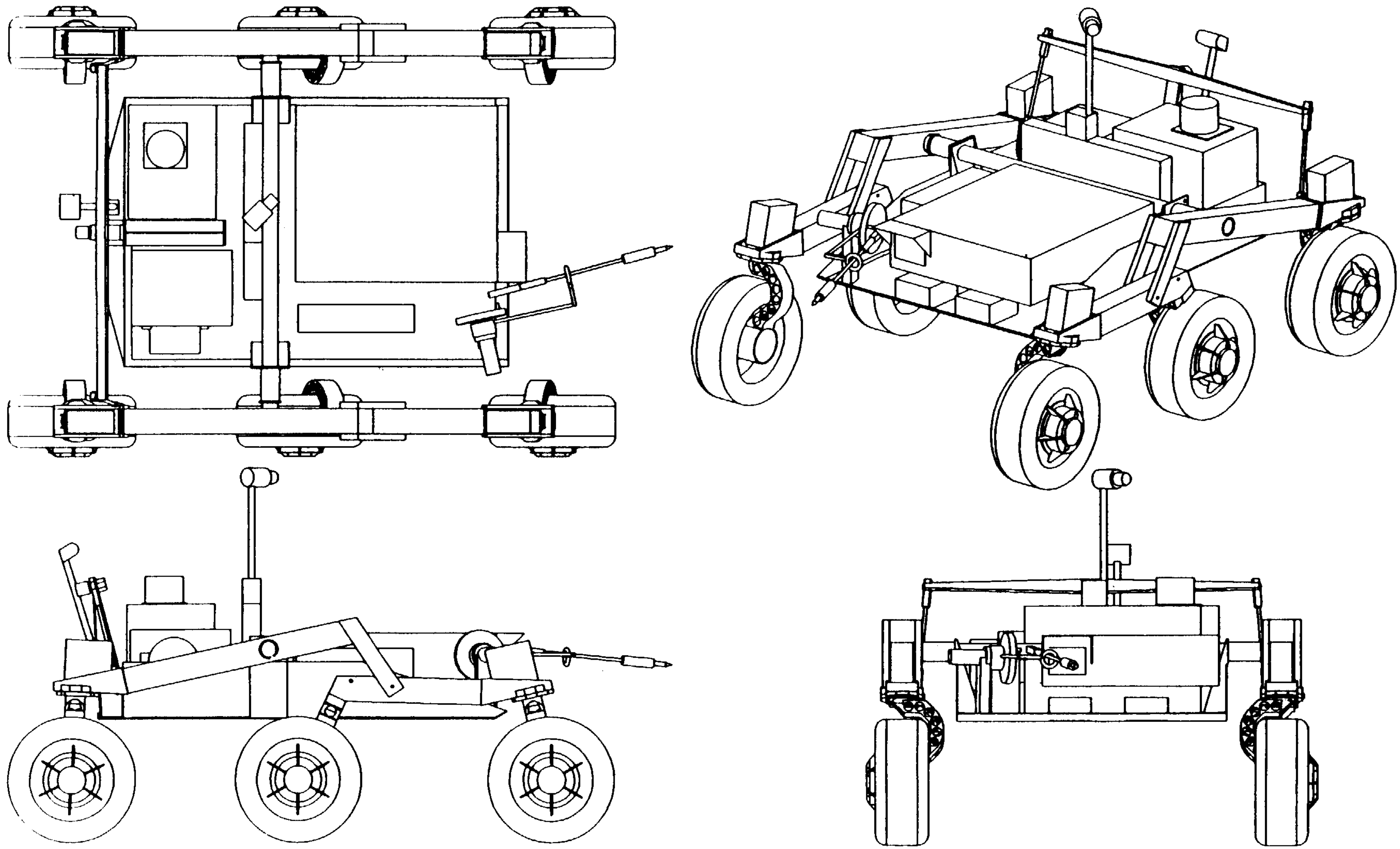

Figure 6. Rocky IV configuration drawings.

Figure 7. Rocky IV in the sandbox.