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ROBOTICS AGE™

RETHINKING ROBOT MOBILITY

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When human beings attempt to solve a problem, they tend to match successful past solutions to the new situation. While this problem solving technique is extremely helpful in day-to-day situations, it can be misleading when we attempt to solve unique new problems. The trouble is that this whole conceptual process is so unconscious that we are unaware of the assumptions we make along the way. The problem of robot mobility is an excellent example.

When we start thinking about robot mobility systems, we immediately catalog the solutions to mobility problems in other fields. Most present-day mobile robots use a version of the mobility system originally designed for either a tricycle, a wheelchair, an automobile, a tank, an all-terrain vehicle, a wagon, or a combination of these. In some cases, the designer has turned to nature for inspiration and the result may resemble a spider or even an elephant.

Many mobile robots are well adapted to the problems they are designed to solve. For example, robots like the Ohio State University (OSU) Hexapod or the Odetics Odex I walker are required for certain rough-terrain applications. In fact, an article by R. B. McGhee, et. al. (see references) shows that walking robots may actually be more efficient than wheels or treads on soft surfaces. Still, it is very important to realize the original problem for which the technique was developed.

Attempting to apply existing vehicle designs to robots quickly points out the difference between the intelligence and sensory capabilities of a robot "driver" and a human operator. The robot driver will be a relatively stupid, nearly blind computer. Expecting a robot driver to perform the classical parallel parking maneuver for an automobile is optimistic in the extreme.

Solutions based on animal models have an additional problem since animals are constructed from different materials than those available for the robot. For example, muscle tissue provides both an excellent lightweight servomechanism, and compliant springiness that can be used to store and recover kinetic energy.

SPECIFICATIONS

Before designing a robot mobility system, we must determine the robot's intended capabilities and make several trade-offs for cost vs. performance.

The first major trade-off is between walking and rolling. While a walking robot can go almost anywhere, it will tend to be very complex mechanically, difficult to control, expensive to build, slow, and (on finished surfaces) relatively inefficient. Some of these difficulties can be eliminated, but only at the expense of making others worse. Depending on the applications, the ability to climb stairs, rubble, and undefined obstacles, may outweigh all other considerations. On the other hand, it may be more economical to replace stairs in the robot's environment with ramps, thus making a rolling robot acceptable.

There are always restrictions on the robot as well. These restrictions include the width and height clearance available, the maximum weight, the damage that it can be permitted to inflict on its running surface, etc.

The required robot capabilities, combined with the necessary restrictions, constitute the robot's *performance envelope*. In order to visualize this performance-matching process, it is helpful to put the requirements into a tabular form, such as Table 1.

Note that Table 1 does not include absolute requirements such as clearance since any approach that cannot meet these requirements is immediately eliminated. Obviously, this table attempts to quantify a qualitative process, but it serves a useful purpose in assuring that all factors are

CAPABILITY	**ABILITY RATING**	**IMPORTANCE MULTIPLIER**	**PRODUCT**
Climb steps	0	0	0
Climb curbs	10	5	50
Steep ramps	10	8	80
Quietness	5	2	10
Cleanliness	5	10	50
Speed	10	4	40
Efficiency	7	8	56
Simple computer control	10	8	80
Movement accuracy	10	6	60
Payload weight	6	5	30
Mar surface	0	−5	0
Damage surface	0	−10	0
Initial cost	5	−4	−20
Maintenance cost	7	−10	−70
Total For Candidate			366

Table 1. Evaluation table for the Synchro-drive robot with chains and retractable legs.

weighed proportionately for each approach. The table also shows where improvements may be needed. Some approaches can be eliminated outright, since they have hopelessly low ratings, while some others will be a tight fit into the envelope.

As the robot design progresses, it is sometimes necessary to back up and modify or subdivide the original performance envelope. For example, two models of the robot may become necessary to fulfill all requirements, or perhaps an ability may be dropped rather than modify the robot's operating environment.

The example used in Table 1 evaluates applications we had in mind for our Cybermation robots and is an approximate evaluation of our first prototype. These robots would be expected to perform teleoperated and autonomous functions in demanding industrial applications, including explosives factories, clean-rooms, and nuclear reactor buildings. Thus, as reflected in the table, initial cost is not as important as the maintenance costs and reliability. The ability to climb steps was dropped in favor of requiring ramps and lifts.

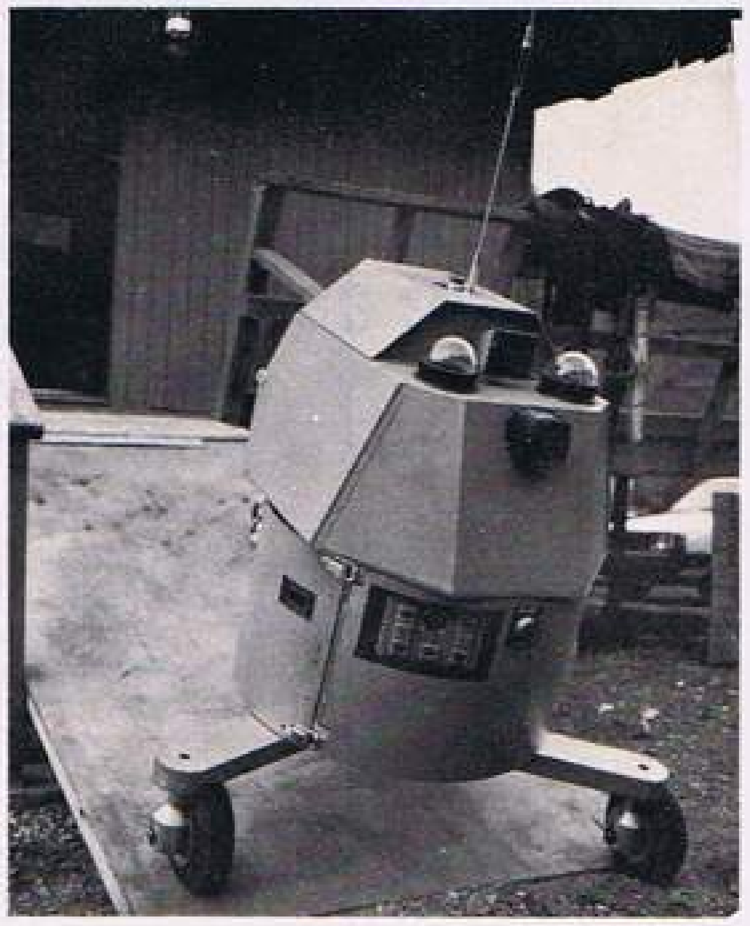


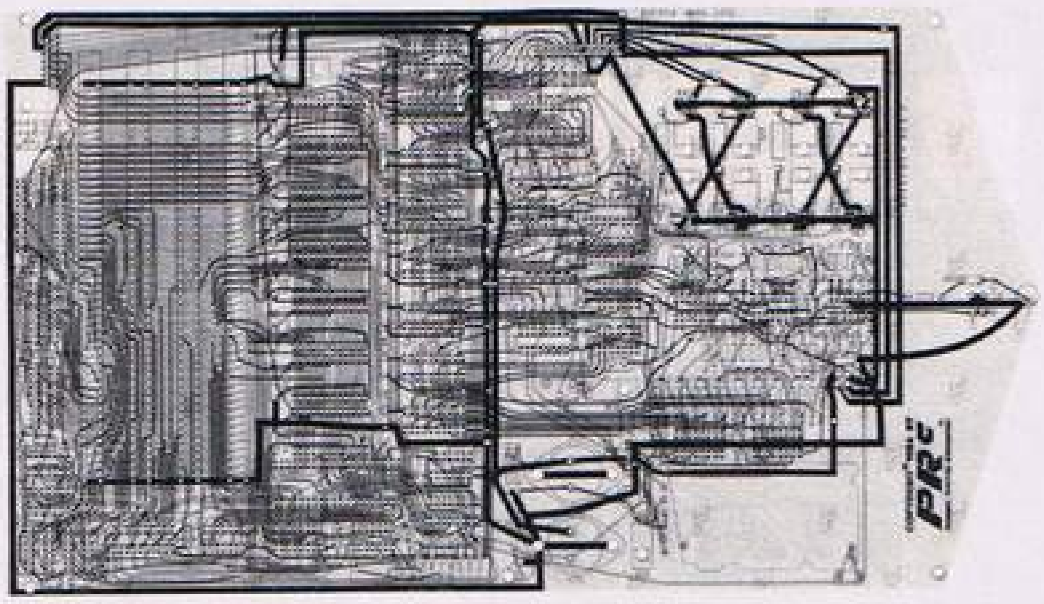
Photo 1. The first Kludge prototype with chain drive and retractable legs.

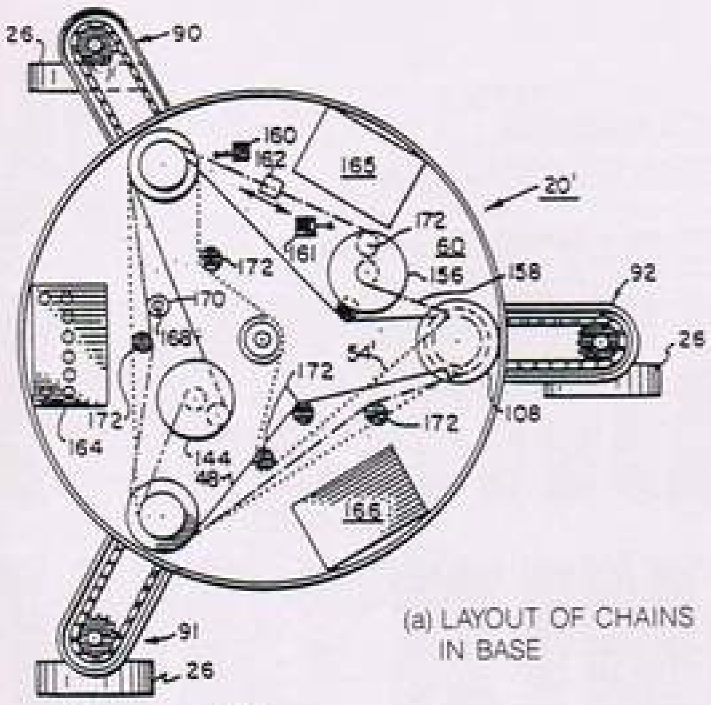
THE SYNCHRO-DRIVE

The base rated in Table 1 is shown in Photo 1 and Figure 1. It consists of three wheel assemblies located on retractable legs. We call this the *Synchro-drive* since a set of chains is used to synchronously steer and drive all three wheels. The robot has three sets of motors, gear boxes, and chains; one for driving the wheels, one for retracting and extending the legs, and one for steering the wheels. Additionally, the steering chain is connected to a *spine* shaft running up through the center of the base. The robot's turret is mounted on a flange attached to this shaft, and rotates with the shaft in such a way that the turret always points in the same direction as the wheels.

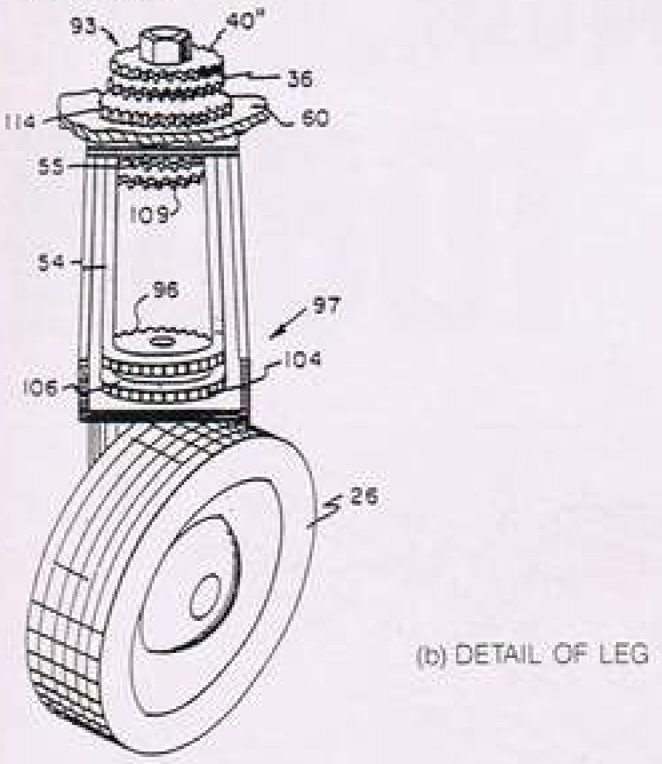
This configuration gives the Synchro-drive some interesting capabilities. For example, the base does not rotate as the robot executes a turn. Not only does this save energy (by not requiring rotational acceleration and deceleration of the base), but it also allows the robot to maintain a sense of direction, by measuring the angle of the turret and base. One of the greatest advantages of the Synchro-drive is that steering and drive commands represent a pure polar coordinate reference system. This greatly simplifies navigation.

Furthermore, since the Synchro-drive has a true zero turning radius, it does not need reverse. This means that rear-facing sensors, and two (expensive) quadrants of the drive motor control can be eliminated.





(a) LAYOUT OF CHAINS IN BASE



(b) DETAIL OF LEG

Figure 1. The Synchro-drive with chains. Figure 1a shows the layout of chains in the base. Figure 1b details an individual leg arrangement.

Finally, the wheel assembly is designed to allow turns without translation. This was accomplished by off-setting the wheel from the center of the steering axis and placing its driving gear in such a way as to impart a rolling action during steering (see Figure 2). The robot can thus turn in place, without damaging carpets, tile, or wood floors.

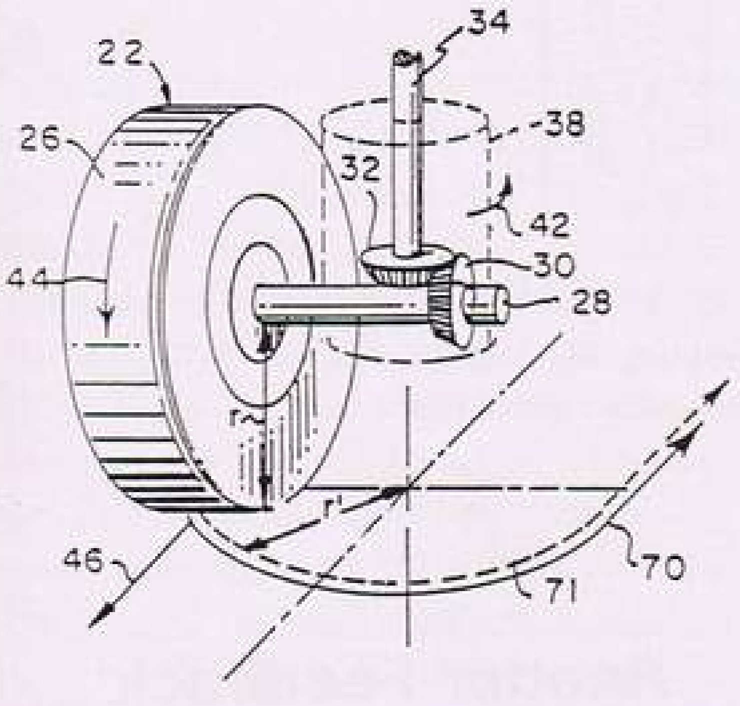


Figure 2. Since the Synchro-drive wheel describes a small arc when it is changing orientation, it does not mar or destroy carpets or polished floors.

The Synchro-drive approach evolved after many (informal) cycles through the evaluation process just described, and yet the approach still had short-comings at the point shown in Table 1.

The prototype (nicknamed Kludge) showed that the basic mode of movement was largely superior to other modes being considered, but the chains were a real problem. First, chains don't like to operate in a horizontal plane, and at least 180 degrees of engagement or *purchase* is required on each sprocket. This meant that many idlers had to be installed, which lowered efficiency and increased costs. Secondly, the chains stretch over time and must be adjusted. Additionally, the chains took up a lot of room and forced the robot's center of gravity to be higher than necessary. As a general rule, chains are noisy and dirty by nature. Finally, the wheels had to be realigned each time the chains were adjusted or tightened.

Each of these problems could be lessened by one measure or another, but the approach kept coming up short of our goals.

USING SHAFTS

The problem then became how to build a robot that had all the good qualities of Kludge but was clean, reliable, easily assembled and repaired, had a lower

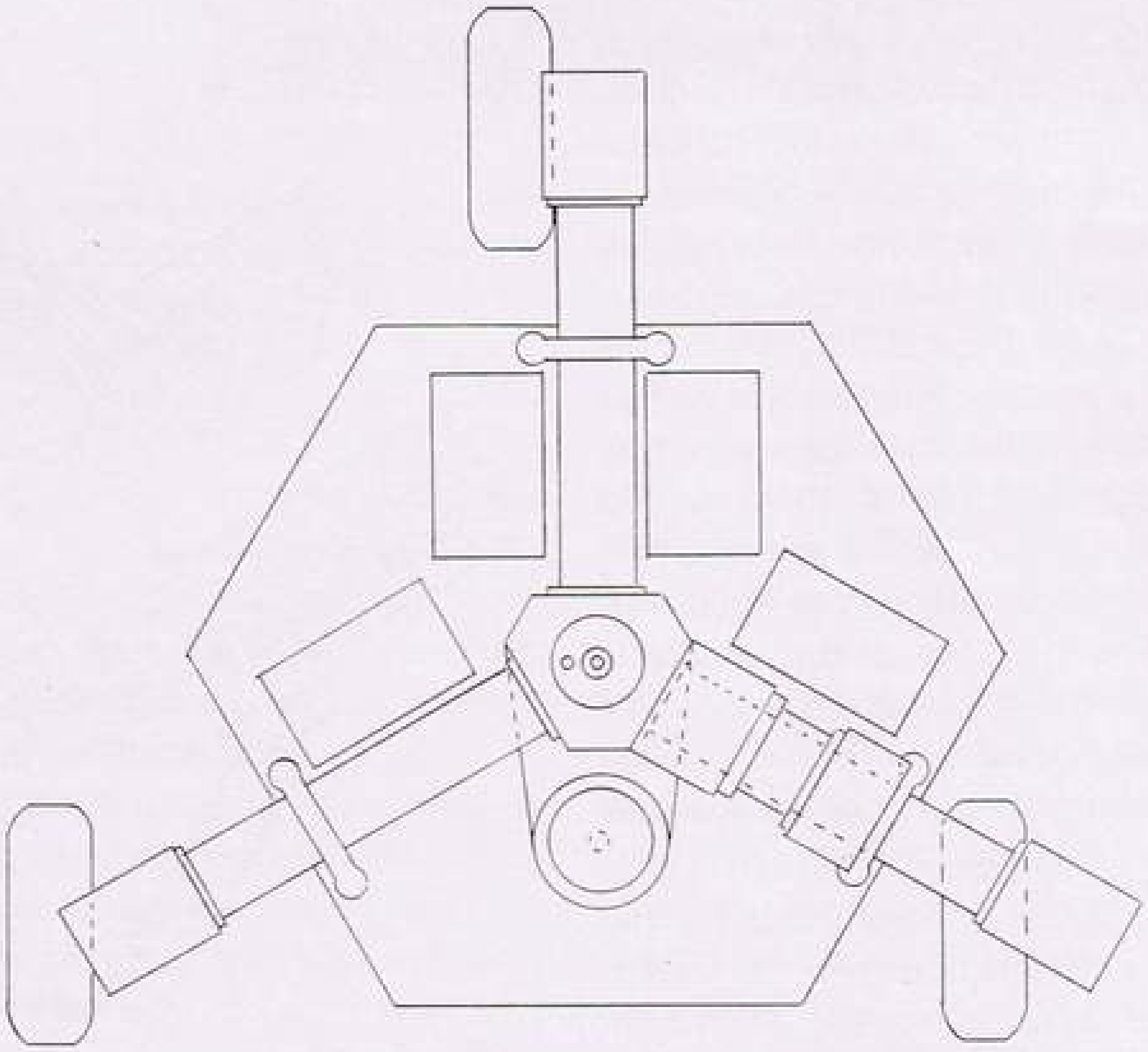


Figure 3. Layout of the Synchro-drive base with concentric shafts.

CAPABILITY	ABILITY RATING	IMPORTANCE MULTIPLIER	PRODUCT
Climb steps	0	0	0
Climb curbs	10	5	50
Steep ramps	8	8	64
Quietness	10	2	20
Cleanliness	10	10	100
Speed	10	4	40
Efficiency	9	8	72
Simple computer control	10	8	80
Movement accuracy	10	6	60
Payload weight	6	5	30
Mar surface	0	−5	0
Damage surface	0	−10	0
Initial cost	4	−4	−16
Maintenance cost	2	−10	−20
Total For Candidate			480

Table 2. Evaluation table for the Synchro-drive robot with concentric shafts and fixed legs.

center of gravity, and required no realignment. It wouldn't hurt if the new approach was (in the jargon of the patent office) clearly *novel* as well. This would allow us to obtain patent protection for the engineering investment.

The solution was to use a unique combination of concentric shafts and bevel gears. With this configuration, the moving parts could be enclosed inside hollow tubes comprising the robot frame members (see Figures 3 and 4). This eliminated pollution, and greatly reduced maintenance. Accurately keyed gears kept the steering in alignment at all times.

The second production prototype (K2A) contains only a handful of different types of bearings and gears that are used repeatedly throughout the design. Furthermore, the new approach allows the batteries, drive motor and gear box to be slung between the leg members, lowering the center of gravity. By doing this, and by extending the fixed legs slightly beyond the edge of the base, the robot is about 80 percent as stable as the first Kludge prototype with its legs fully extended, and about 160 percent as stable as the first prototype with its legs retracted. Although an extensible-leg version using concentric shafts is planned, the cost savings on the current model outweigh the loss of high-end stability, at least for most current applications.

The result of these improvements is shown in Table 2. Notice that for the relatively small loss of stability, the savings in other areas are substantial. As an additional advantage, the maneuver required for extending and retracting the legs was eliminated.

CONCLUSION

The emergence of mobile robots as an important economic reality will require the rethinking of the basic precepts of mobility. These new mechanical "beasties" will encompass an enormous variety of forms, each governed by the niche it is intended to fill. Exactly as in nature, those robots that best fill the requirements of their niche will flourish and evolve, and those that are hastily or ill-conceived will become extinct.

We have used the Cybermation Synchro-drive as an example, but the basic process of fitting a solution to the problem can be used in the development of any robotic system.

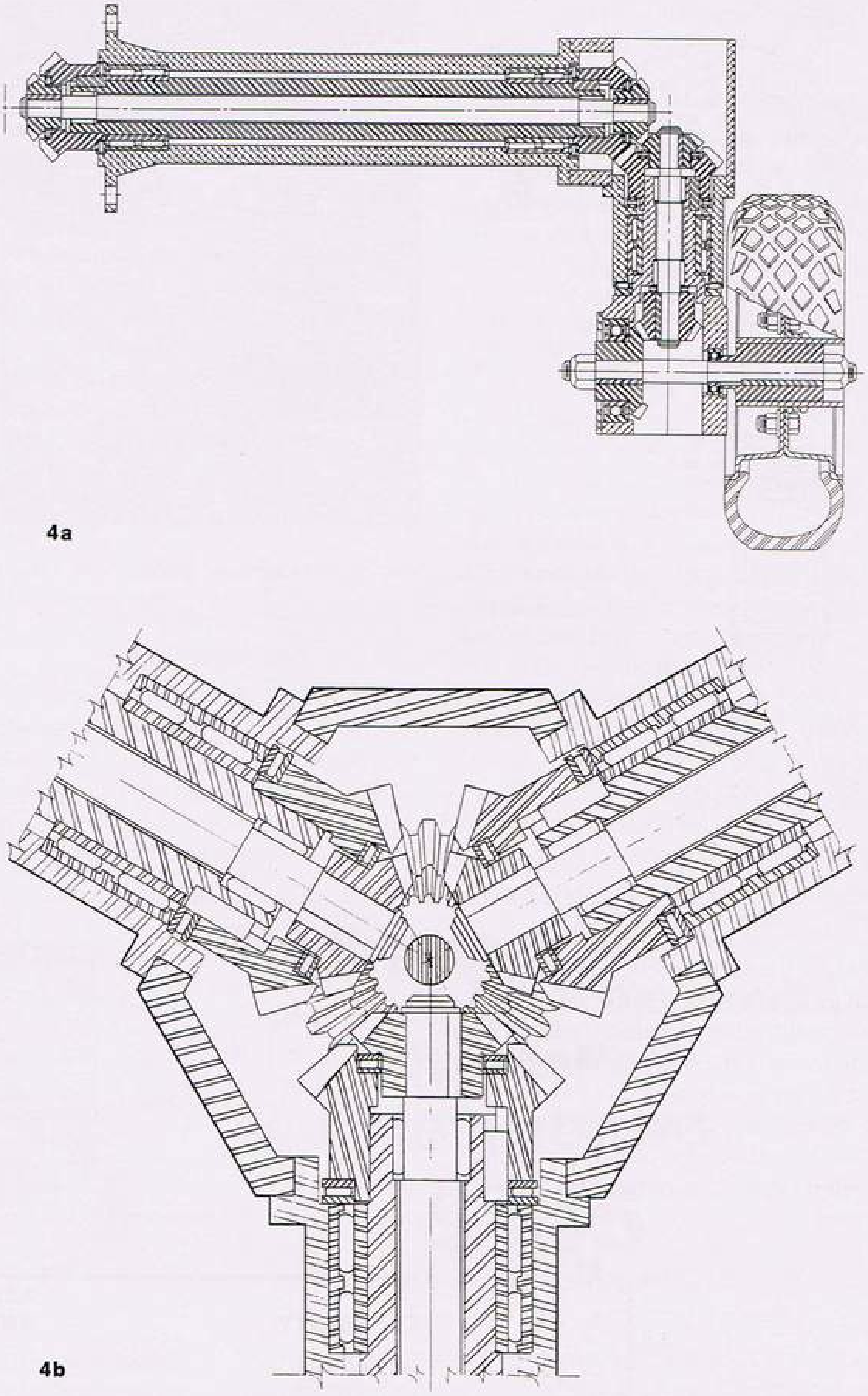


Figure 4. Detail of the Synchro-drive base with concentric shafts. Figure 4a shows the concentric-shaft driven leg. Figure 4b shows the leg junction at the center of the Synchro-drive base.

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