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COMPLIANT-LINKAGE KINEMATIC DESIGN FOR MULTI-DEGREE-OF-FREEDOM MOBILE ROBOTS

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ABSTRACT

Multi-degree-of-freedom (MDOF) vehicles have many potential advantages over conventional (i.e., 2-DOF) vehicles. For example, MDOF vehicles can travel sideways and they can negotiate tight turns more easily. In addition, some MDOF designs provide better payload capability, better traction, and improved static and dynamic stability. However, MDOF vehicles with more than three degrees-of-freedom are difficult to control because of their overconstrained nature. These difficulties translate into severe wheel slippage or jerky motion under certain driving conditions. In the past, these problems limited the use of MDOF vehicles to applications where the vehicle would follow a guide-wire, which would correct wheel slippage and control errors. By contrast, autonomous or semi-autonomous mobile robots usually rely on dead-reckoning between periodic absolute position updates and their performance is diminished by excessive wheel slippage.

This paper introduces a new concept in the kinematic design of MDOF vehicles. This concept is based on the provision of a *compliant linkage* between drive wheels or drive axles. Simulations and experimental results show that compliant linkage allows to overcome the control problems found in conventional MDOF vehicles and reduces the amount of wheel slippage to the same level (or less) than the amount of slippage found on a comparable 2-DOF vehicle.

1. Introduction

Automated guided vehicles (AGVs) are finding increasing use in many industrial applications. Conventionally, AGVs use floor-embedded wires for guidance, but a few emerging applications use *autonomous mobile robots* (AMRs) [Hollingum 1991]. Applications in hazardous environments (such as nuclear power plants or radioactive waste storage sites) call for *remotely* *controlled robots* (RCRs). Throughout this paper we will call AGVs, AMRs, and RCRs collectively *vehicles*.

Most conventional vehicles use either a *differential drive* design (i.e., two drive wheels, each with its own motor [Borenstein and Koren, 1985; Pritschow et al, 1988]), or a *tricycle* design where one wheel is steered and driven [Hammond, G., 1986; Wiklund et al., 1988]. Such vehicles are easy to control and are more maneuverable than, for example, automobiles. However, in many applications floor space is limited and vehicles with even better maneuverability would help save floor space, especially in *existing* environments that were not originally designed for automatic vehicles.

One smart design that improves maneuverability is the so-called *synchro-drive* [Cybermotion; Denning]. Synchro-drive vehicles typically have three driven and steered wheels that are mechanically linked to one drive motor and one steer motor (i.e., these vehicles are still 2-DOF). The three wheels can be steered into any direction, but are parallel to each other at all times. While this design allows the vehicle to move in all directions, there is no control over the orientation of the vehicle body (since only the wheels turn).

Full control over travel direction *and* orientation can be achieved by utilizing a type of special wheels that can roll sideways [Leifer et al., 1988; Feng et al., 1989; Killough and Pin, 1992]. Such vehicles, usually driven by three or four independent drive motors, are useful in some applications but cannot be used efficiently on any but smooth and regular surfaces [Feng et al., 1989]. Since most industrial applications don't provide such smooth surfaces, we will limit the following discussion to *multi-degree-of-freedom* (MDOF) vehicles with full-sized, "conventional" wheels.

MDOF vehicles could be considered ideal for transport tasks in confined space. Theoretically, MDOF vehicles are extremely maneuverable; they are capable of turning in confined space, moving sideways, and performing other maneuvers that would allow the vehicle to move along a mathematically optimal trajectory. A good MDOF design could significantly reduce the amount of floor space required for safe vehicle operation.

Although a vehicle with more than two independently controlled axis offers exceptional advantages in terms of maneuverability, it also causes exceptional difficulties in terms of control. Section 2 describes the nature of these difficulties in greater detail, and Section 3 introduces the concept of *compliant linkage* and presents two different 4-DOF designs that implement *compliant linkage*. Section 4 briefly describes the control system and Section 5 shows simulation results.

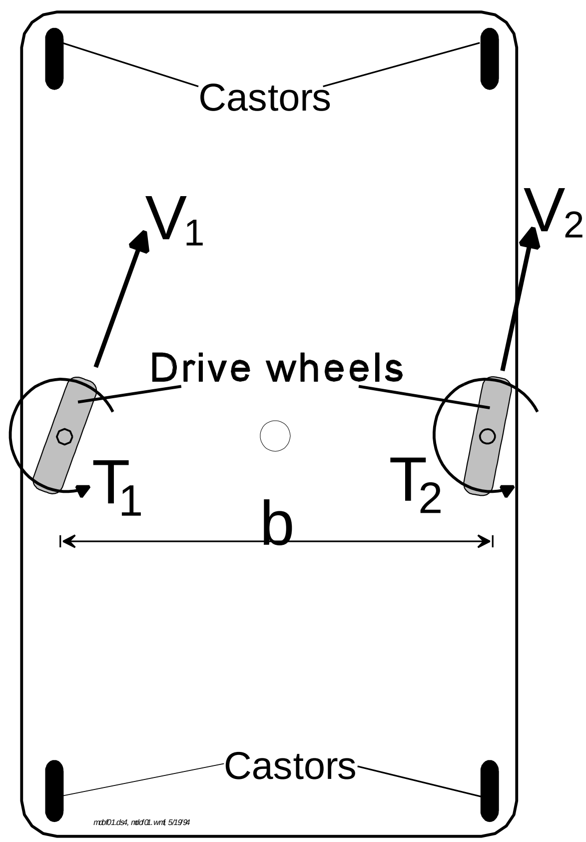

Figure 1: Four-degree-of-freedom vehicle.

2. Background

One typical design of a MDOF vehicle is the *four-degree-of-freedom* (4-DOF) vehicle shown in Fig. 1. An actually existing prototype based on this design is HERMIES-III, a vehicle that was developed and built at the Oak Ridge National Laboratory (ORNL) as part of an ongoing multi-million dollar project of the Department of Energy (DOE). The author as well as researchers from three other universities participates in this project.

HERMIES-III has two *tricycle* drives, each with one drive and one steering motor. Four castors at the vehicle corners provide stability. Although HERMIES-III is a very advanced and exceptionally well-designed system, researchers at ORNL [Reister, 1991, Reister et al, 1991] reported on large position errors after certain maneuvers, thought to be caused by severe wheel slippage.

The problems observed with HERMIES-III are representative for a wide variety of kinematic designs and the difficulties in the control and positioning of MDOF vehicles are not limited to the particular design of HERMIES-III. Similar problems with PLUTO (a 6-DOF vehicle developed at Carnegie-Mellon University) were reported by H. Moravec, one of the leading researchers in Mobile Robots. In a technical report Moravec [1984] describes his observations at the end of a three-year development effort as follows:

> *"...severe oscillations and other errors in servoing the drive and steering motors."*

and

> *"With all [motor assemblies] running the robot mostly shook and made grinding noises."*

A thorough analysis of the nature of these problems revealed that they could be remedied by introducing a novel kinematic design and control system. Before we present such a design in Section 3 we will discuss some of the problems in more detail.

<u>The Instantaneous Center of Rotation (ICR) for Trajectory Control</u>

One effective way to control the trajectory of a MDOF vehicle is based on the concept of the *instantaneous center of rotation* (ICR). Although this method is not new [Evans et al., 1990; Reister, 1991], it is described here to illustrate typical requirements for a MDOF vehicle.

With the ICR method it may be assumed that a higher-level trajectory planner has determined that points **A** and **B** on the vehicle should *momentarily* travel in the directions α and, as indicated in Fig. 2. A trajectory like the one in Fig. 2 can be prescribed by a *guide-wire* in AGV applications, or an obstacle avoidance system in AMR applications [Borenstein and Raschke, 1991].

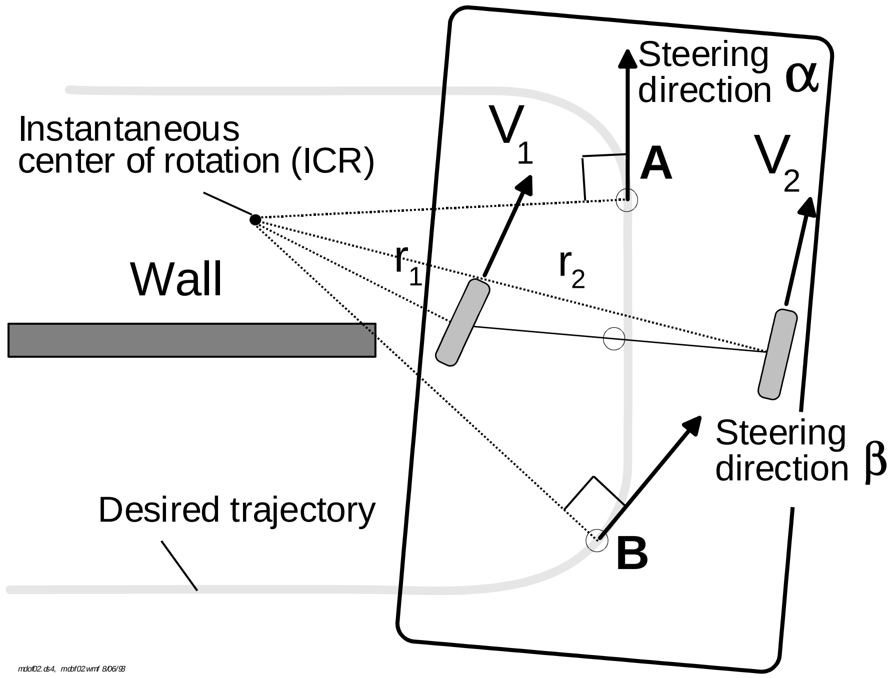

Figure 2: Controlling a 4-DOF vehicle by *Instantaneous Center of Rotation*.

The ICR concept is borrowed from the areas of machine design and kinematics: it is an imaginary point around which a rigid body appears to be rotating *momentarily* (for an instance *dt*), when the body is rotating *and* translating. In pure translatory motion, the ICR is located at a distance ∞ from the body. One special case of translatory motion exists when both wheels are parallel to the longitudinal axis of motion. This configuration corresponds to the widely used *differential drive* where two wheels are located on the same axes but are driven by individual motors. We will call this the *normal* configuration, and, by contrast, we will use the term *crabbing* when at least one wheel is not oriented parallel to the longitudinal axes of the vehicle.

For the vehicle in Fig. 2, The ICR is constructed as the crosspoint of the two normals to the steering directions. Then, the orientation of the two wheels is set normal to the two position vectors r_1 and r_2. Clearly, this orientation of the drive-wheels *will* cause rotation around the ICR and, consequently, rotation around the ICR results in points **A** and **B** *momentarily* moving in the required steering directions. However, the velocities of the wheels must maintain the ratio

$$\frac{V_1}{V_2} = \frac{r_1}{r_2} \qquad (1)$$

Note that V_1 will be *independent* from V_2 when $r_1 = r_2 = \infty$ (i.e., in *normal* configuration). It is also important to point out that the ICR concept can be applied to vehicles with any number of degrees of freedom (e.g., 4 drive/4 steer kinematics).

The problem with MDOF vehicles is that Eq. (1) must be met *accurately* (i.e., the ratio between the two velocities must be maintained), for otherwise *wheel slippage* will occur. Unfortunately, conventional DC-motor velocity control loops do not *precisely* follow the prescribed velocity profile during transients. Yet, even the smallest temporary deviation from the prescribed velocity profile will result in a violation of Eq. (1) and therefore cause wheel slippage.

Since such deviations are inevitable, even with the best possible controller, **we conclude that a means for implementing *mechanical compliance* must be designed into any MDOF vehicle**. Such mechanical compliance can accommodate temporary velocity deviations until the controllers catch up to correct the problem.

Existing MDOF vehicles like PLUTO or HERMIES-III do not have an *intentionally* designed mechanical compliance. Consequently, those vehicles may either "rattle" and "shake" as they try to accommodate position errors through *unintentional* compliance such as backlash, or they may suffer from extensive slippage.

3. The Concept of Compliant Linkage

The key element in any workable MDOF design must be the provision of *mechanical compliance*. In this paper we will concentrate on 4-DOF designs, although the concept can be implemented in general by mounting all but one drive wheel such that each wheel may slide freely in the desired direction of compliance.

One possible implementation is shown in Fig. 3. This vehicle has two independent *drive assemblies* (or *chassis*) that are free to rotate about a vertical shaft connected to the chassis. Each *chassis* comprises of two drive motors, along with their respective reduction gears, encoders, and drive wheels. Each pair of drive wheels is located on a common axes and forms a *differential drive system* capable of moving forward, backward, and rotating – simply by controlling the velocities of the drive wheels. Each *chassis* also holds two castors, for stability when traveling sideways.

One unique aspect of this vehicle is the combination of two *differential drive systems* into a *dual differential drive* (DDD) vehicle. Another unique aspect is the *longitudinal slider*, a linear bearing that allows relative motion (compliance) between the front and rear chassis.

Besides the encoders that are attached to each one of the drive motors, three additional encoders are needed: one each on the vertical shafts, and one linear encoder on the *longitudinal slider*.

Fig. 4 shows the *compliant linkage* implemented in a *dual tricycle drive* (DTD) design like the one in Fig. 1. This design is probably less expensive, because it doesn't require the two additional rotary encoders on shafts **A** and **B**, as shown in Fig. 3.

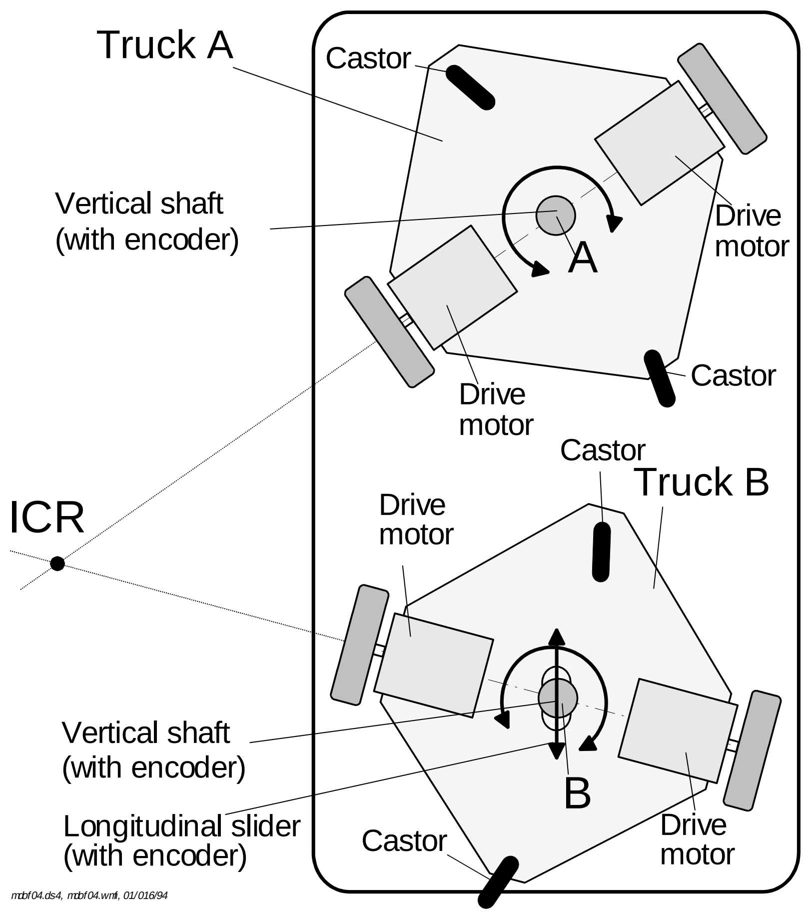

Figure 3: A 4-DOF *dual differential drive* vehicle with *compliant linkage*.

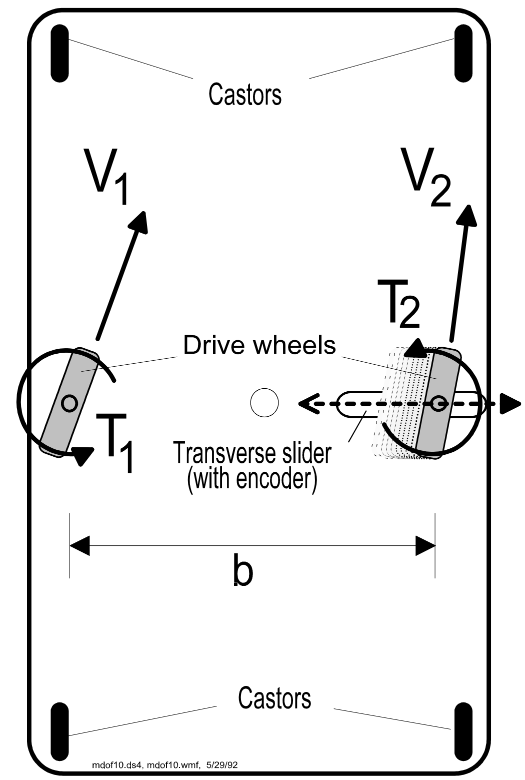

Figure 4: Design of a *dual tricycle drive* (DTD) vehicle with *compliant linkage*.

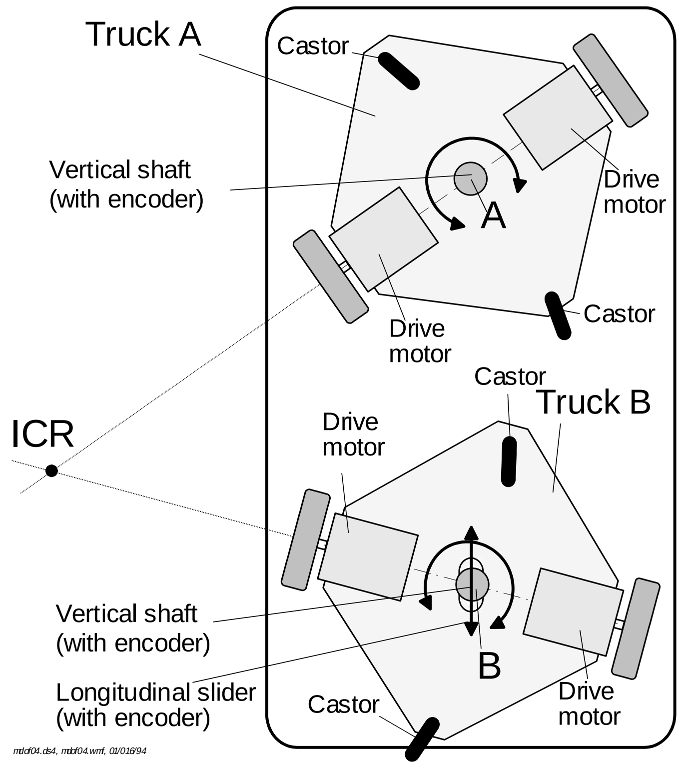

Figure 5: A 4-DOF *dual differential drive* vehicle with *compliant linkage*.

4. The Controller

The controller for the 4-DOF vehicle is implemented in software and runs on a 386/20 MHz computer. It comprises of the functional components shown in Fig. 5. For simplicity these components are described only in terms of the DDD vehicle.

4.1 Chassis Level Controller

The task of this controller is to maintain the proper **speed ratio** between the left and right drive wheel of each chassis. The implementation of this controller is based on the *cross-coupling* control method developed earlier by Borenstein and Koren [1987].

4.2 Vehicle Level Controller

This controller is designed to minimize deviations from the nominal length of the *compliant link* that connects the two chassis'. For this purpose, the controller must adjust the *relative speed* between the two chassis'. The relative speed, in turn, is governed by the absolute speed of the chassis **and** its orientation relative to the link. This creates a difficulty that can be visualized by considering the two extreme cases: (a) both chassis are facing 90° sideways. In this case, the relative speed is always zero, and the link-length can only be controlled by changing the orientation of either chassis; (b) both chassis' are aligned longitudinally and the link-length can **only** be controlled by changing the speed of the chassis-motors.

4.3 Trajectory Interpolator

The trajectory interpolator is designed to generate reference velocity signals that would result in a specific trajectory for the vehicle (for example, the one shown in Fig. 2). The ICR method described in Section 2 is only one possibility to implement a trajectory interpolator, and it is suitable for automatic vehicle operation. Since there are many applications in which a human operator remotely steers the vehicle, or has to program a trajectory explicitly for the vehicle, this interpolator is designed to allow a human operator to control robot motion with a 3-DOF joystick, in a more intuitive way than the ICR method does. This interpolator translates joystick x or y deflections into linear Cartesian coordinate motion (e.g., an x-deflection will cause pure sideways crabbing, and a y-deflection will cause pure forward travel). The third axis, θ, will cause pure rotation. A further refinement is an *alignment* option, where the θ-axis is used to specify an *absolute* orientation with which the vehicle attempts to align at all times. This option is convenient for the operator when, for example, the vehicle travels through a narrow corridor, or when the vehicle emerges from a corridor with a known orientation of, say, ρ=90º, and then traverses

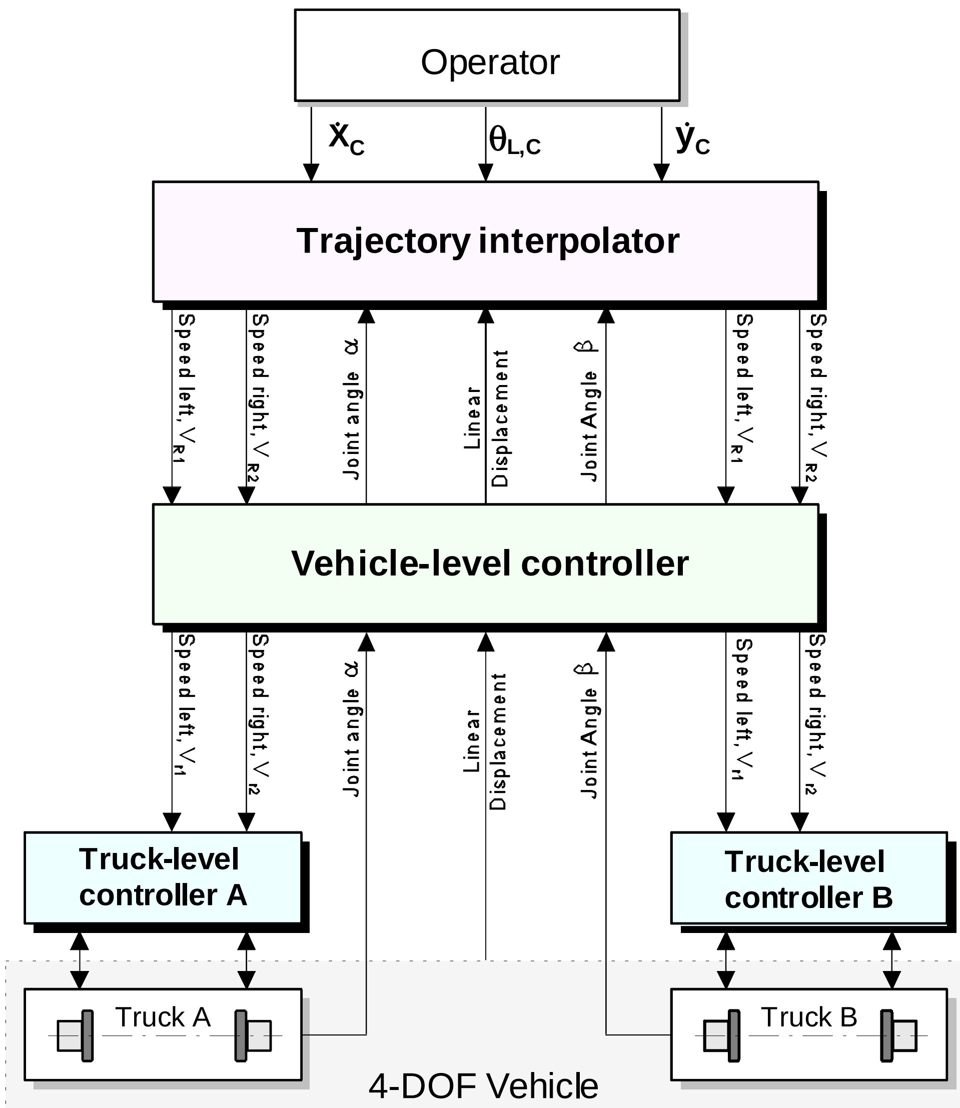

Figure 6: Major components of the MDOF vehicle control system.

an open workspace to dock with a station at $\rho=120^{o}$. In this case the operator would only need to adjust the θ-axis to 120^{o}; the interpolator takes care of the alignment while the operator steers the vehicle toward the docking station, using only x and y commands.

5. Simulation Results

The critical question in determining the feasibility of the 4-DOF vehicle is the performance of the *Vehicle Level Controller*. A suitable indicator for the performance of the *Vehicle Level Controller* is the *fluctuation* of the length of the *compliant link*, ΔL. We suppose that the vehicle is feasible if the controllers remain stable under all reasonable driving conditions and if ΔL remains small, relative to the vehicle size. Larger fluctuations would probably be difficult to accommodate from an engineering point of view.

5.1 Simulation results with the *dual-differential drive* (DDD) design

To test the feasibility of the DDD design, a comprehensive simulation program was written. This program includes all the components identified in Fig. 6. Fig. 7 shows a typical run of the simulated 4-DOF vehicle. Special attention was paid to the fluctuations of the *compliant link*, ΔL (see plot in Fig. 7). As can be seen, "dramatic" steering maneuvers cause fluctuations in ΔL, but are all well-within a reasonable range.

Another set of conclusions that can be drawn from observing ΔL is the feasibility of **conventional** MDOF systems. As we can see in Fig. 6, ΔL is *significant* (even with a finely tuned control system). The actual values of ΔL give a rough estimate of the amount of slippage that a vehicle **without** mechanical compliance would suffer.

5.2 Simulation results with the *dual tricycle drive* (DTD) design

The behavior of a DTD vehicle was tested with the help of a simulation program, similar to the one discussed in Section 5.1. The result of a DTD run is shown in Fig. 7. One subjective impression from simulation runs with both the DDD and DTD designs is that the latter appears to be slightly less stable when performing maneuvers that involve fast changes in the orientation of the vehicle. In practice, this may require the control program to reduce the speed during such maneuvers, to avoid excessive fluctuations in *link-length*. For example, during maneuvers 2 and 5 (see Fig. 7) the forward speed of the vehicle had to be reduced (i.e., only a small amount of translatory motion could be superimposed on the vehicle rotation), if larger *link-length* fluctuations were to be avoided. We also observed somewhat larger oscillations during fully sideways crabbing (maneuvers 3 and 7). Nonetheless, the results clearly show that both designs are feasible. Furthermore we believe that the performance of both designs can be improved substantially by optimizing the *Trajectory Interpolators* for each case.

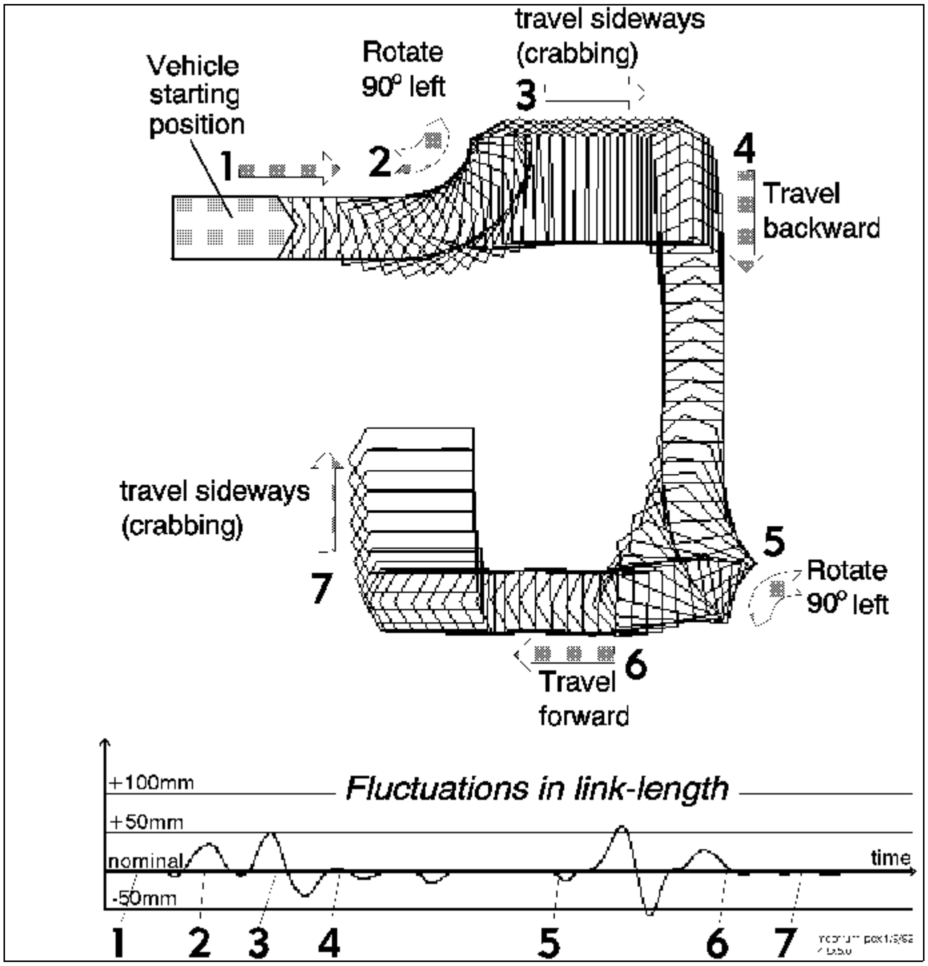

Figure 7:
Simulation run with the *dual differential drive* (DDD) vehicle from Fig. 3.

6. Conclusions

Four-DOF vehicles with *compliant linkage* provide mobility modes that permit movement through tightly constrained environments. This feature is of great importance for applications in Nuclear Power Plants [DOE-91] and in Nuclear Waste Storage facilities [DOE-90]. The *dual differential drive* design is particularly beneficial for these applications because it provides **actuator redundancy**, that is, the ability to function in the event that **one motor** (or even **both** motors of the same axle) fails. In this case, both wheels of the axle are disengaged (like a "neutral" gear in automobiles) while the remaining axle with two controlled motors provides full motion capability. With this capability, the mobile robot can still perform many tasks, or, at the very least, retrieve **itself** from an operation. Actuator redundancy was identified as one of seven key *Technical Task Areas* in a request for proposals issued by Sandia National Laboratories.

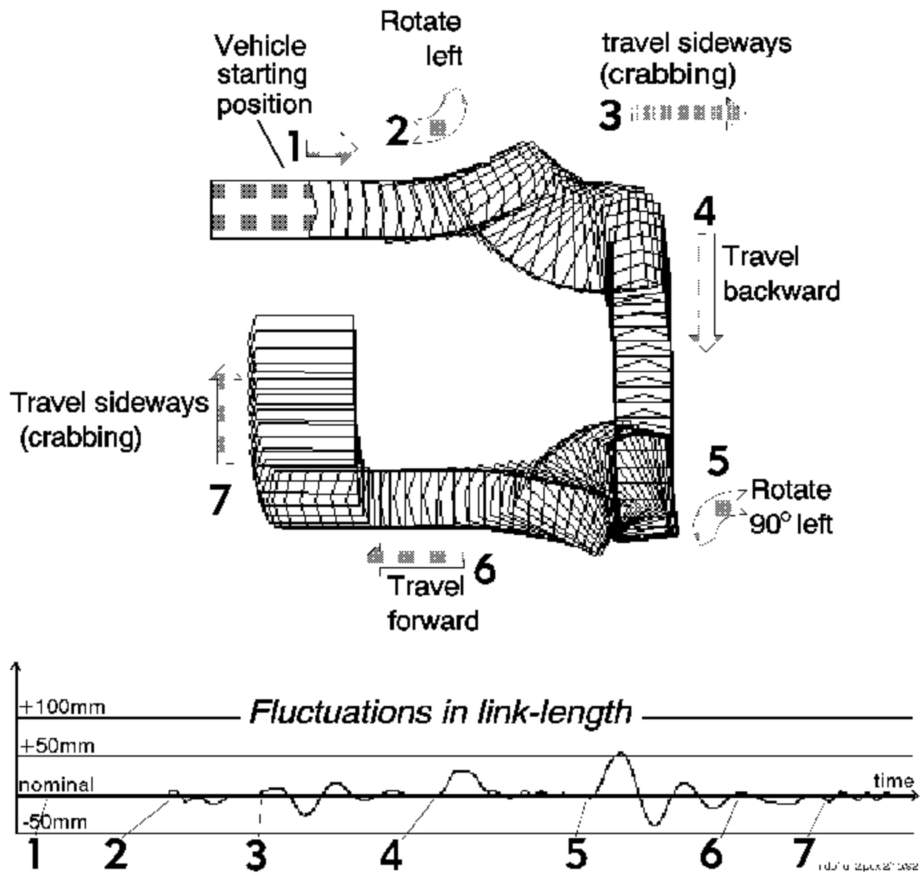

Figure 8: Simulation run of the *dual tricycle drive* vehicle from Fig. 4.

The substantially better dead-reckoning ability of *compliant linkage* vehicles makes it possible to implement the automatic alignment feature (discussed in Section 4.3). This is an innovative form of *operator assistance* in operator controlled vehicles. Automatic alignment is beneficial in remote-operator applications as well as in applications where the operator is actually riding on the vehicle.

The concept of *compliant linkage* provides substantially improved dead-reckoning accuracy and is therefore essential for the operation of autonomous or semi-autonomous multi-degree-of-freedom vehicles.

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