National Workshop for Research on Transportation Cyber-Physical Systems: automotive, Aviation and Rail

Position Paper

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Active control of the interaction between a vehicle wheel and the road surface is now well established in automotive vehicle systems. In the form of antilock braking systems and traction control systems it is in large volume production. The use of active suspension technology is less widespread, but is an established feature of high-end vehicles. Active suspension technology has also been shown to have benefits in rough road conditions [1]. What has not been done has been to take full advantage of the potential of active suspensions to improve mobility in unimproved terrain conditions.

According to the U.S. Army, roughly one half of the Earth's land surface is not accessible to conventional off-road vehicles because it is too steep, too heavily vegetated, or too marshy [3]. Much of the inaccessible half is easily negotiated by people and animals using legged locomotion. The use of active suspension capability, together with independent wheel drives provides a means of extending the mobility of wheeled vehicles into this inaccessible region, and doing so in a less environmentally disruptive fashion than by building graded roads.

The problem of coordinating a vehicle with full active suspension capability can be viewed as being analogous to that of coordinating an industrial robot programmed in point-to-point mode. There the desired trajectory of the end-effector between programmed positions is given and the problem is to compute the corresponding joint rates as a function of position in order to appropriately command the joint servos to generate that trajectory. The vehicle problem is: given a desired motion of the vehicle body, whether commanded by an on-board operator, or by an autonomous guidance system, compute the corresponding torques and forces to be commanded of the wheel motors and suspension actuators to generate the desired trajectory of the vehicle body.

Depending on the number of wheels used, such vehicles are under-constrained by from two to ten or more degrees of freedom. This situation offers the opportunity to optimize the performance of the vehicle whether by maximizing its traction when climbing over obstacles on a slope, maximizing static and/or dynamic stability, distributing the load as evenly as possible to minimize the chance of failure of the wheel-ground contact in weak soil, or by addressing other operationally important criteria. The appropriate performance parameters to optimize can be expected to vary with the terrain conditions and the vehicle's functional objectives [2, 4]. It is, therefore, necessary to have a flexibly reconfigurable coordination system.

This capability requires pervasive computation at all levels of the vehicle architecture. One might think about three functional levels that interact intensively. The upper level accepts commands from an on-board operator, and/or gathers data from exteroceptive sensors in order to localize the vehicle and model the terrain in order to select a trajectory along which the vehicle will be commanded to progress. In the presence of significant obstacles this layer might also select from a library, or otherwise generate an appropriate behavior to negotiate the obstacle. The middle layer gathers data from an inertial measurement unit, or equivalent, along with proprioceptive sensors that monitor actuator force and position etc. It translates the desired vehicle trajectory into actuator commands while implementing algorithms that optimize the performance of the vehicle's interaction with the environment, as briefly outlined above. The lower level performs servo control of the actuators to achieve the commanded values as nearly as possible.

Potential applications are diverse ranging from planetary rovers and military vehicles to silviculture and mobility enhancement for handicapped individuals.

The principal research challenges include:

> Development of sufficient understanding of the mechanics of interaction of vehicles with obstacles to design appropriate crossing strategies for a vehicle of given geometry and actuator characteristics.
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> Development and testing of effective coordination software architectures, with the ability to adapt to changing terrain conditions and performance objectives.
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> Development of methods of on-line modeling of the terrain in front of the vehicle, and of appropriately responding to the model presented. This needs to be flexible since the model must be continuously updated as occluded areas become visible to sensors, and as the coefficient of friction and other relevant mechanical properties can be evaluated by contact.
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> Development of better means of characterizing the geometry and mechanical properties of natural terrain to enable high fidelity simulation for purposes of design optimization, design of maneuvers and/or training of neural computing processors.

The above discussion is directed by the Workshop's focus on automotive, aviation and rail systems. However, if we think more broadly about ground transportation systems legged locomotion becomes a possibility. This has the potential to be a breakthrough innovation since it removes the need to create roads, as we know them, at least in areas where transportation can be dominated by legged systems. It is often forgotten that the most severe impacts on natural environments start with the construction of roads. Despite considerable research effort over the past decades we are still far from being able to produce a robust and flexible legged system for mobility in unimproved terrain. The challenges run from development of actuation systems that can efficiently produce the short duration, controlled force pulses needed to drive such systems, through development of systems to rapidly and robustly model the terrain in front of the vehicle based on sensor data, to invention of suitable algorithms for robustly coordinating dynamically running vehicles. it may be noted that many of the challenges for legged vehicles are very similar to those for actively coordinated wheeled systems, as described above.

The research challenges include those listed above, but also include development of actuators capable of efficiently generating controlled impulses over short duty cycles, and algorithms for decoupling control axes in dynamic, multi-legged locomotion.

References

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Biographical Summary

Dr. Waldron obtained the degrees of Bachelor of Engineering and Master of Engineering Science from the University of Sydney (Australia). He received his PhD from Stanford University in 1969. He was also awarded the degree of Doctor of Engineering by the University of Sydney in 1999. After a period with Australian Iron and Steel Pty. Ltd. he has held teaching appointments at Stanford, the University of New South Wales, and the University of Houston, before joining The Ohio State University in 1979. He served as department chairman from April 1st, 1993 to June 30th, 2000. He joined Stanford University on September 1st, 2000.

Dr. Waldron's research interests include geometric, mechanical and software design of robots and computer coordinated mechanical systems. He has a particular interest in locomotory biomechanics and in the design of computer coordinated vehicles and robotic systems for use in unstructured environments.

Dr. Waldron was the Editor of the *ASME Transactions Journal of Mechanical Design* from 1988 through 1992. He has authored over 320 journal articles and conference proceedings. He is co-author, with G.L. Kinzel, of the text Kinematics, Dynamics and Design of Machinery, published by John Wiley and Sons (1998, 2003), and with S. M. Song, of the book Machines that Walk: The Adaptive Suspension Vehicle published by M. I. T. Press (1988). He has edited three other books.

Dr. Waldron is a Fellow of The American Society of Mechanical Engineers and a Senior member of IEEE. He is immediately Past Technical Leader of the ASME Systems and Design Group and Past President of IFToMM the International Federation for Promotion of Mechanism and Machine Science. He received the ASME Leonardo da Vinci Award in March 1988, the Mechanisms Award in 1990, the Machine Design Award in 1994, the Ruth and Joel Spira Outstanding Design Educator Award in 2002, the Dedicated Service Award in 2004 and the Abbott Award in 2008. He also received the Joseph F. Engelberger Award of the Robotic Industries Association in 1997.