

Fused Dynamics of Unmanned Ground Vehicle Systems

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ABSTRACT

Through inverse dynamics-based modeling and computer simulations for a 6×6 Unmanned Ground Vehicle (UGV) - a 6×6 truck - in stochastic terrain conditions, this paper analytically presents a coupled impact of different driveline system configurations and a suspension design on vehicle dynamics, including vehicle mobility, and energy efficiency. A new approach in this research work involves an estimation of each axle contribution to the level of potential mobility loss/increase and/or energy consumption increase/reduction.

As it is shown, the drive axles of the vehicle interfere with the vehicle's dynamics through the distribution of the wheels' normal reactions and wheel torques. The interference causes the independent system dynamics to become operationally coupled/fused and thus diminishes vehicle mobility and energy efficiency. The analysis is done by the use of new mobility indices and energy efficiency indices which are functionally coupled/fused. Four possible scenarios are considered to trade between mobility and energy efficiency improvements by redistributing power between the drive axles in severe/extreme terrain conditions, including poor friction coefficient conditions, and high longitudinal and lateral slopes. Potential design improvements to de-couple (de-fuse) dynamics of the two systems are also discussed.

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OPERATIONAL FUSION OF VEHICLE SYSTEM DYNAMICS

Over the past several decades, the term "fusion" has become a key word in the Information Technology and Mechatronics research field. Originally, fusion was related to sensors, data, and information. These three terms can be presented as either synonyms or different kinds of knowledge [1, 2].

Many discussions on the exact meaning of the term "fusion" have been held. At first, fusion was defined as a "combination of data and information from a single and multiple sources" [3], and later became a "process designed to manage (i.e., organize, combine and interpret) data and information, obtained from a variety of sources" [4]. These and many other definitions were presented and analyzed, as well as a newly proposed definition: "Information fusion is the study of efficient methods for automatically or semi-automatically transforming information from different sources and different points in the time into a representation that provides effective support for human or automatic decision making" [5].

Despite different definitions of fusion, a significant research effort was undertaken to formalize classes of systems for information fusion and develop a formal theory of fusion including data fusion, feature fusion, decision fusion, and fusion of relational information [2]. Much work was devoted to fusion-related technical issues in vehicle engineering. Applications of sensor, data, and information fusion for vehicle and transportation engineering are generally found in the following areas:

- Intelligent transportation systems and transportation infrastructure;
- In-vehicle diagnosis, prognosis and maintenance,
- Security and safety systems, entertainment systems and
- New mechatronics-based designs of chassis and powertrain systems related to vehicle motion and task fulfillment control.

In the intelligent transportation area, the main focus related to fusion is on road telematics and telecommunication, vehicle localization and navigation systems, road network control, traffic data management with the purpose to improve passenger safety, and reduce transportation time and fuel consumption [6]. A fuzzy multi-sensor data fusion helps reduce the failure of an integrated vehicle health maintenance system [7].

As examples for information fusion in vehicle security and safety areas, the following publications can be mentioned: a multimodal method suggested for in-vehicle driver identification [8], driver's maneuver recognition [9], driver distraction [10], target vehicle detection [11], vehicle collision warning [12], and a target-tracking scheme for autonomous vehicle navigation [13], etc. Additionally, several directions in the area of chassis and powertrain systems, in which "fusion" is the key word, were formed related to vehicle motion and task fulfillment control of manned and unmanned ground vehicles. A few examples for these directions include: a wireless data fusion to position agricultural vehicles for precision farming tasks [14], multi-sensor fusion to estimate the position, orientation, and velocity of a steerable four-wheel industrial vehicle [15].

Integration of various sensors and sharing of sensor information will be essential in future control systems in order to minimize cost while maximizing the data that these sensors provide [16]. It was emphasized in [17] that integrated control can result in performance degradation when two or more controls operate together. Hence, a judicious integration of individual chassis control systems was undertaken in this reference to push the overall vehicle performance further to its limit by providing synergetic braking and suspension control integration for maximum stability in highly dynamic maneuvers. Recently emerged control allocation applications to vehicles can make a solid basis to distributing control to different levels [18]. However, the problem of the system dynamics intrusion, i.e., potential negative impact on each other's performance, is still out of the scope of current capabilities. Usually, control allocations introduce weight factors in a cost function.

A group of publications are devoted to fusion-related technical issues in open architecture-type of systems. In paper [19], architecture of by-wire systems is discussed with an emphasis on hardware and software distribution, and a communication medium to exchange information among different vehicle systems. The exchange of information between the systems becomes critical in system integration applied to complex in-vehicle networks [20]. As underlined in [21], data flow and data-software architecture can become common problems in future system designs with open architecture. Another conclusion can be deduced from an analysis of research work done in the vehicle engineering field: fusion processes in vehicle system dynamics have not been systematically considered and researched. Fusion, as a coupling or merging (can be both positive and negative) of system dynamics, needs special attention and new research methods.

The operational fusion of vehicle system dynamics is considered in this paper as a passive operational coupling/ fusion of vehicle system dynamics. The passive fusion can exist without "permission." When designing vehicle systems, engineers usually are not concerned about a potential passive fusion of different systems. It is typically hidden in the design process. Indeed, when one department designs a suspension and another designs a differential, a fused system dynamics might show up in an undesirable way somewhere during a test. It is much easier to prevent negative consequences of the passive fusion if mathematical models of the systems' dynamic's pre-emptively describe fused effects of the systems' to analyze the merged effect of the coupled/fused dynamics.

The passive fusion can be recognized at an earlier stage of a system mathematical modeling and computer simulations. Previously in paper [22], the nature of passive coupling between the driveline and suspension system dynamics was presented. However, further research work discovered an influence of the fused dynamics on both unmanned ground vehicle mobility and energy efficiency, and thus required a more systematic approach to research the fused dynamics for the two systems. A set/sequence of research steps was used in this paper to study operational fusion of the driveline and A-frame suspension systems for a 6×6 terrain truck:

1. Derive the equations for the truck's normal and longitudinal dynamics and constraints which are imposed by the driveline and suspension systems on truck dynamics;
2. Analyze the equations from item 1 to find the parameters/ characteristics that represent both systems. List and study these systems' parameters and characteristics that are coupled, and thus generate a merged impact of the truck's motion;
3. Study contributions of these parameters/characteristics to the vehicle's operational properties by analyzing the equations from item 1. This study and analysis will explain the mechanical physics of the influence of the joint effect for the driveline and suspension systems' vehicle properties. Additionally through this study, find a combination(s) of parameters that mitigate a negative impact of the passive fusion of dynamics of the driveline and suspension systems'.

The following sections present details on the above-listed three items to understand the stochastic fused/coupled dynamics, operational fusion research of the driveline and suspension systems, and its influence on the truck's energy efficiency and mobility.

MODEL OF TRUCK LONGITUDINAL AND NORMAL STOCHASTIC FUSED DYNAMICS

Figures 1 and 2 are diagrams to understand the layouts of the A-Frame suspension - driveline - truck system. Also, the applied forces and reactions, as well as geometric parameters are clearly understood from the diagrams.

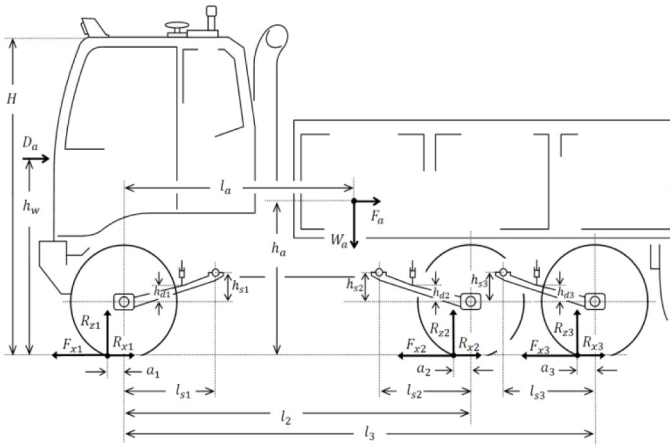


Figure 1. 2D drawing of a 6x6 terrain truck with A-Frame suspension and geometry on a horizontal surface

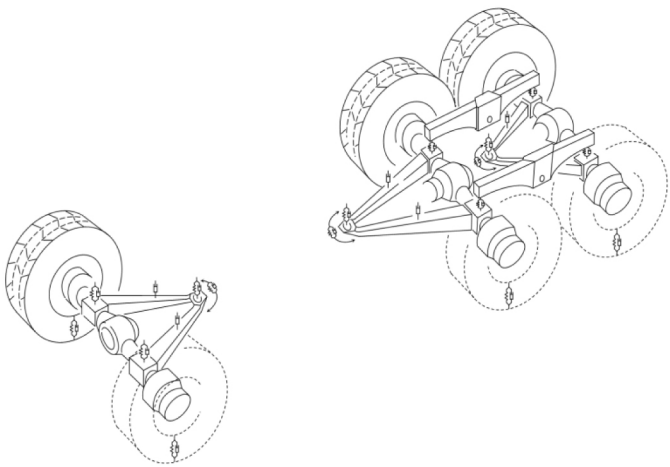


Figure 2. 3D drawing of a 6x6 terrain truck's driveline with A-Frame suspension

These diagrams were used to compile equations of truck normal and longitudinal dynamics using the inverse dynamics approach. It should be emphasized that a 3-D truck math model was developed and the truck's longitudinal dynamics is described by the equation:

$$F_{x\Sigma} = \sum_{i=1}^3 F_{xi}^{('')} = \sum_{i=1}^3 R_{xi}^{('')} \pm W_a \sin \theta_n + D_a + F_a \delta_r \quad (1)$$

Here, θ_n is the longitudinal slope angle (not shown in Fig.1); ' and '' denote the left and right wheels respectively. Equation (1) determines the total circumferential force of the truck which is needed to overcome the total resistance to motion specified in the right-hand side of equation (1). The three components of the total resistance to motion are considered including the longitudinal component of the truck's weight, $W_a \sin \theta_n$, air drag force (D_a), and inertia force (F_a). Indeed, the inverse dynamics approach specifies the truck's velocity profile which is typical for terrain multi-wheel drive vehicles [25] (presented in Fig. 3); which makes D_a and F_a known factors.

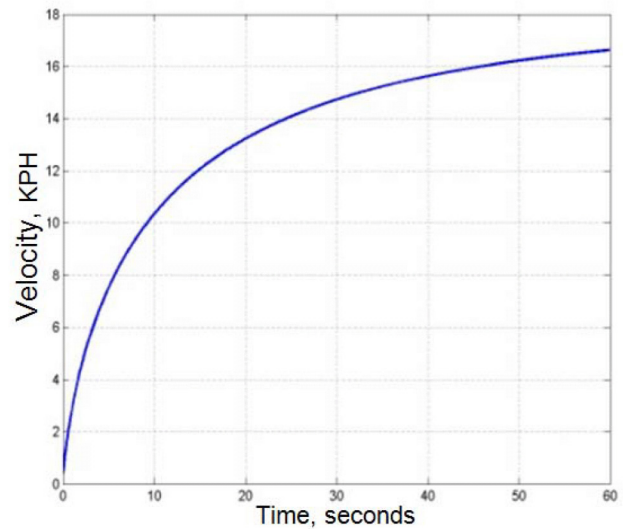


Figure 3. Truck's velocity profile

Stochastic terrain topographical characteristics were introduced by the macro- and micro-profiles. The macro-profile was represented by the longitudinal slope angle, θ_n , and the length of a slope, l_n . Stochastic values for angle θ_n determine the magnitude and direction of $W_a \sin \theta_n$ in equation (1).

The first components on the right side of equation (1), the rolling resistance forces of the wheels ($R_{xi}^{('')}$), depend of the wheels' normal reactions and rolling resistance coefficients ($f_i^{('')}$), which are different for each wheel and depend on the tire-terrain interactions.

$$R_{xi}^{('')} = R_{zi}^{('')} f_i^{('')}, \quad i = 1 \dots 3 \quad (2)$$

Stochastic rolling resistance coefficients were simulated using a method presented in paper [23, 24]. The dynamic normal reactions of the wheels ($R_{zi}^{('')}$) are considered here as an algebraic summation of the (i) static normal reactions ($R_{zi}^{st}{}^{('')}$) computed for a motion under the given velocity profile on a smooth surface (see Fig. 3), and (ii) dynamic components due to vibrations of the sprung mass and un-sprung masses of the truck generated by the terrain micro-profile:

$$R_{zi}^{('')} = R_{zi}^{st}{}^{('')} + K_{tsi}^{('')} (\xi_i^{('')} - q_i^{('')}) + C_{tsi}^{('')} (\dot{\xi}_i^{('')} - \dot{q}_i^{('')}), \quad i = 1 \dots 3 \quad (3)$$

here, $K_{tsi}^{('')}$ and $C_{tsi}^{('')}$ are the reduced stiffness and damping of a tire-terrain system, $q_i^{('')}$ is the height of the micro-profile, and $\xi_i^{('')}$ is the translational displacement of an un-sprung mass, which are determined from dynamic equations of vibrations of these masses (Fig. 2). Static components $R_{zi}^{st}{}^{('')}$ are computed [22] (written using notations in Fig. 1):