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GUN-TURRET MODELLING AND CONTROL

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Abstract. *In this work, we study the problem of gun-turret control of an armored combat vehicle. We develop a complete, fully coupled dynamic model with seven degrees of freedom, dealing properly with nonholonomic constraints. The parameters for simulation are based on a Leopard 1A1 tank and obtained by 3-dimensional modelling and by experimental methods. A feedback linearization control scheme is applied, with gains obtained by an optimal control approach. Besides, we implement a typical linear control law based on angular rate signals. Simulation results indicate comparative performance differences between the linear and the nonlinear control schemes.*

Keywords: *gun-turret, mobile robot, nonlinear control, combat automation.*

1. Introduction

The problem of controlling a combat vehicle's gun-turret aim is very important in combat automation and a critical technology for new developments in work by the Brazilian Army S&T branch. Nonetheless, the problem is fundamentally the same as the one of mobile manipulator control, what broadens the applications of the results steaming from this research.

The gun-turret control is achieved through proper combined actuation of its azimuth and elevation inputs, which compensates for the perturbations due to the vehicle's motion. We choose to cast such problem as one of mobile manipulator control, using methodology of this field in order to derive the dynamic model, devise a trajectory generation scheme and designing a nonlinear control law, which is based in feedback linearization, specifically dynamic inversion, and optimal control.

Nonholonomic constraints are dealt with by choosing a reduced set of independent coordinates, the path coordinates, and the required parameters are obtained through a hybrid computer modelling and experimental method. A snapshot of the vehicle's computer model is shown in Fig.1.

The proposed nonlinear control law is favorably compared against a typical linear control, as indicated by the simulation results shown.

This paper is organized as follows. In section 2 we present a literature review, in section 3 we briefly discuss the modelling methodology, in section 4 we present the proposed control scheme and show illustrative simulation results and in section 6 we close with the conclusion.

2. Literature Review

It is worth remarking that the field of gun-turret is very sensitive to the defense industry and establishment and not much detailed and complete work has been published.

The first studies in the field date from the 60s (Ogorkiewicz, 1991). Works as the ones of Dhir et al (1994), Dhir et al (1997), Salter et al (1998), Wong (1997), Shabana et al (1998) and Slättengren (2000) are representative of the field's progress.

With the goal of rejecting motion perturbations, Dana et al (1992) consider the full system - chassis, turret and gun, although dynamic uncoupled. Lin et al (1993) and Tao et al (1999) emphasize control design for simple dynamic models to which are added nonlinearities such as friction and flexibility. In another work, Tao et al (2000) introduce an optimal control scheme with feedback linearization, but the vehicle's and the gun's dynamics are kept uncoupled.

Banks et al (1994) use the dynamic model of the ATB-100, a US Army testbed, and employ three control techniques: robust control applied to a linearized model, nonlinear control and intelligent control. Others, such as Zhang et al (1993) and Arambel et al (2001) also take the same model to test hybrid-optimal control and pseudo bang-bang-control laws.

Arambel et al (2001), working with high velocity gun-turrets, combine a PD control with high-gains in the inner-loop and a nonlinear control in the outer-loop in order to avoid overshooting and high-frequency oscillations.

In Brazil, a sole reference was known before this research effort, which is the work of Leite (2002): "*Influência do Comportamento Dinâmico de um Carro de Combate na Estabilização do Sistema Torre-Canhão*", where the dynamic model increases in complexity from a single mass-spring-dumper up to a very complex fourteen wheel vehicle. The gun-turret's hydraulic system is modelled in detail using bond graphs. A simple PD control is implemented to investigate its

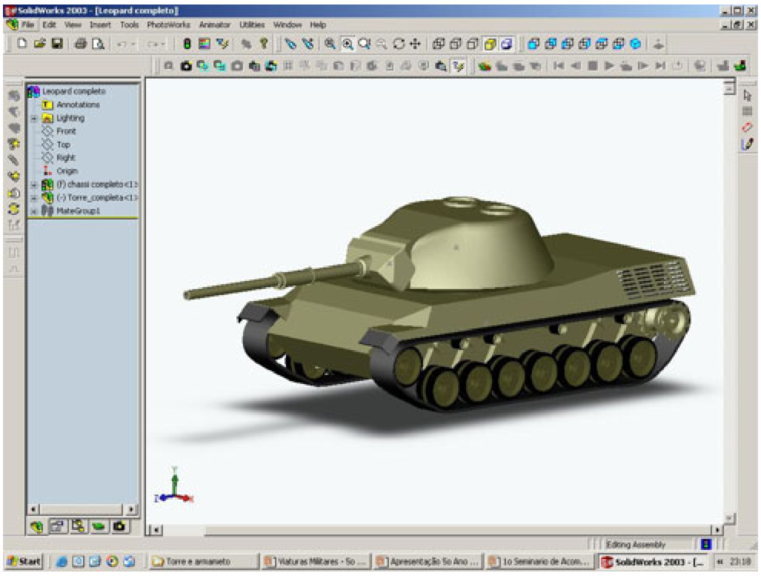

Figure 1. Leopard 1A1 computer model.

sensibility to model parameter variations. The conclusions reached indicate that the gun-turret CG position relative to the vehicle and the gun's CG offset are very important design characteristics. Such special points are shown in Fig.2.

After the work of Leite, there was a preliminary research along the lines of this paper, reported by Gomes and Ferreira (2003), and a more extensive and deep study may be found in Gomes (2004).

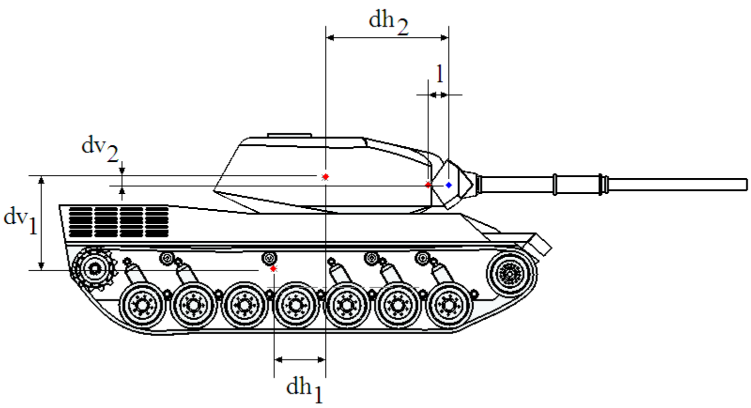

Figure 2. Distances of interest.

In another front, some of the earliest works in mobile manipulator control treated the problem as quasi-static, but it was realized that the resulting errors were not neglectable (Dubowsky et al, 1989). Then, Hootsmans et al (1991) introduced a suspension model and developed a control algorithm called transposed Jacobian, which incorporates the platform mobility.

Following control evolution, Yamamoto et al (1996) employ feedback linearization to a nonlinear dynamic model, and Chung et al (1999) applied a robust control to a mobile manipulator to avoid parameter uncertainty and wheel slipping. Papadopoulos et al (2000), with an approach similar to our choice in this work, employed dynamic inversion for simultaneous trajectory following for the manipulator and the mobile platform underneath it.

Regarding to mobile manipulator dynamic model, Chen et al (1997) use the direct Newton-Euler method and introduce the nonholonomic constraints as centripetal forces. Moving on to indirect methods, Colbaugh (1998) choose to partitionate the dynamics into two sets: manipulator coordinates and platform coordinates, dealing with the platforms no skidding constraints as nonholonomic constraints augmented to the dynamic model by Lagrange multipliers. Others (Papadopoulos et al 2000; Dong et al 2000; Yamamoto et al, 1996, Dong, 2002, Lin et al, 2002) also employed Lagrange multipliers, but eventually reduced the coordinates to an unconstrained set.

3. Modelling

To derive the dynamic model we break it into three subsystems: platform or chassis, turret (1st link) and gun (2nd link), and assume that the platform has differential steering and is mounted on a suspension.

We choose to deal with the nonholonomic constraint picking a set of reduced unconstrained coordinates for the platform's horizontal motion, which is the set of path coordinates s and θ_{yaw}. The s coordinate corresponds to the length of the arc described by the platform's CG horizontal trajectory and $\dot{s}$ is the corresponding velocity in the longitudinal direction.

The platforms suspension allows for three movements: bounce, roll and pitch. The rolling motion is assumed to be small, as typically is in combat vehicles, and the corresponding lateral velocity of the platform's CG is neglected in order to comply with the nonholonomic constraint.

Mounted on the platform is the manipulator (gun-turret), which exhibits an azimuth angle rotation between chassis and turret and an elevation angle between turret and gun.

Therefore, the dynamic model has seven degrees-of freedom (7 DOF) as illustrated in Fig. 3.

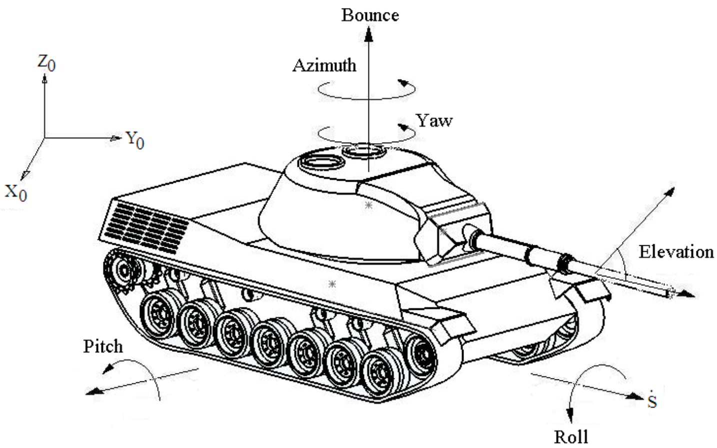

Figure 3. Combat vehicle's degrees of freedom.

Hence, the mobile manipulator's (combat vehicle) coordinates vector is given by

$$\mathbf{q} = \left[\begin{array}{ccccccc} s & z_{Plat} & \theta_{yaw} & \theta_{pitch} & \theta_{roll} & \theta_{azm} & \theta_{elv} \end{array} \right]^T. \tag{1}$$

To derive the equations of motion, at first we look at the direct kinematics to find the linear and angular velocities associated to each of the bodies CG frames and derive the Jacobian matrices. Next the inertia properties are determined, allowing to assembly the full system Lagragian and apply the Euler equations. As the resulting expressions are too cumbersome to show here, the reader is referred to Gomes (2004) for details.

Assuming that the chassis's motion is perfectly controlled by its driver, following a given trajectory, then the manipulators (gun-turret) equations take the form:

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}}_M + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}}_M + \mathbf{g}(\mathbf{q}) = \tau_M + \mathbf{w}, \tag{2}$$

where,

$$\begin{aligned} \mathbf{q}_M &= \left[\begin{array}{cc} \theta_{azm} & \theta_{elv} \end{array} \right]^T \\ \tau_M &= \left[\begin{array}{cc} \tau_{azm} & \tau_{elv} \end{array} \right]^T \end{aligned} \tag{3}$$

and **w** is a known perturbation coming from the dynamic coupling with the platform's motion.

The model's parameters were determined by a hybrid computer-experimental method, as they were partitioned into two groups: inertial and suspension properties. The first group of parameters had its values estimated by building a three-dimensional computer model, developed in Solidworks (Dassault Systemes S.A.) and begin with the work of Dias Jr et al (2002). Having done that, we proceeded to experiment with the suspension system, taking advantage of the vehicle's attitude sensor complemented by a set of accelerometers, in order to find its response to given inputs and eventually identifying its suspension equivalent stiffness and dumping coefficients. Again the reader is referred to Gomes (2004) for details.

4. Control

In this work , we show the results for the implementation of two control laws: one based on dynamic inversion with the gains for the resulting linear error dynamics computed by an optimal control approach, as in Gomes and Ferreira (2003), and another based on typical gun-turret linear control, which amounts to a PI control having the gun-turret's angular rates as states.

The block diagram shown in Fig.4 represents the overall control picture.

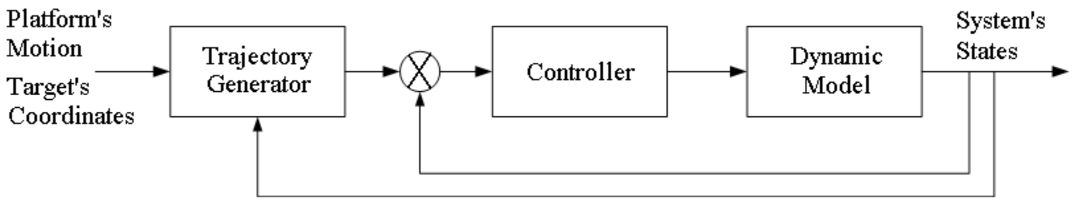

Figure 4. Control block diagram.

The trajectory generation consists of solving the inverse kinematics, taking into account the vehicle's motion and the target's position, resulting in a reference trajectory to be tracked.

We choose to show here the following situation, inspired by an actual training procedure. The combat vehicle is subject to a sinusoidal trajectory in flat horizontal terrain while keeping a constant speed of $\simeq 20km/h$. The trajectory is shown in Fig. 5, and the corresponding pitch and roll angles are shown in Fig. 6 and 7.

During such maneuver the gun should keep aiming at a target at (1500m,0m,1.1375m). To better access such scenario, we should note that, if uncorrected, the pitch error shown could build an error in the vertical aim up to 30m. In addition, we consider that the maximum admissible elevation error is 0.003 rad.

Some simulation results are shown in Fig. 8 through 11. From these, as expected, we notice a better performance of the nonlinear controller, which shows slightly smaller torques and is the only to keep within the error limit.

The linear control performance is mostly degraded by a building up residual error that is due to the control structure, which is in fact a PD control as the state feedback is the angular rate instead of the angle itself. This characteristic has been kept as it reflects the actual Leopard 1A1 setup. We should also remark that the specific situation is somewhat favorable to the linear controller, and worse performance of it should be expected in more demanding scenarios.

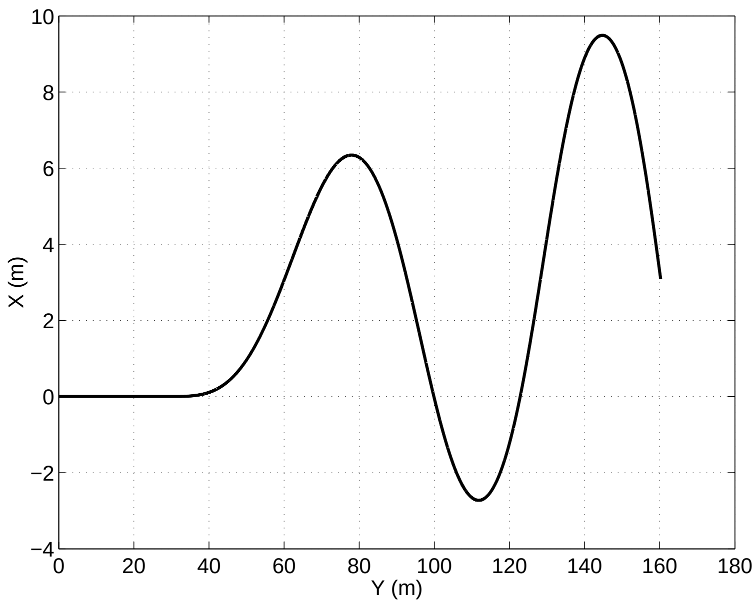

Figure 5. Combat vehicle's XY trajectory.

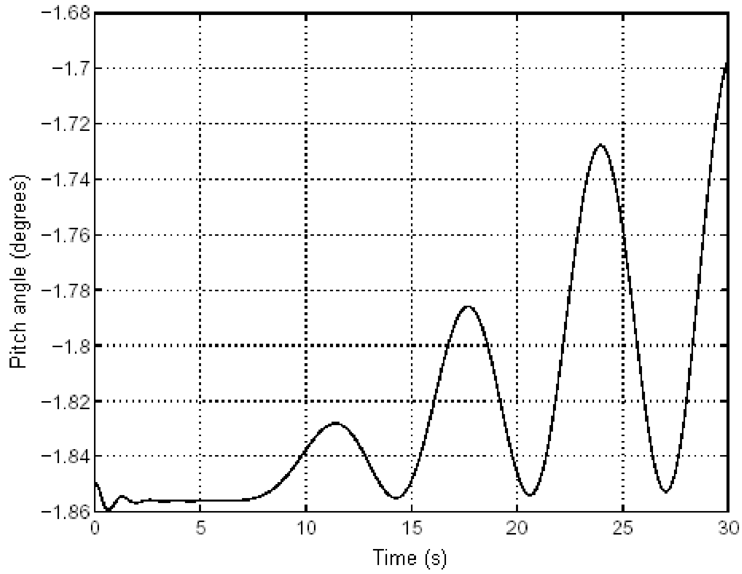

Figure 6. Combat vehicle's pitch.

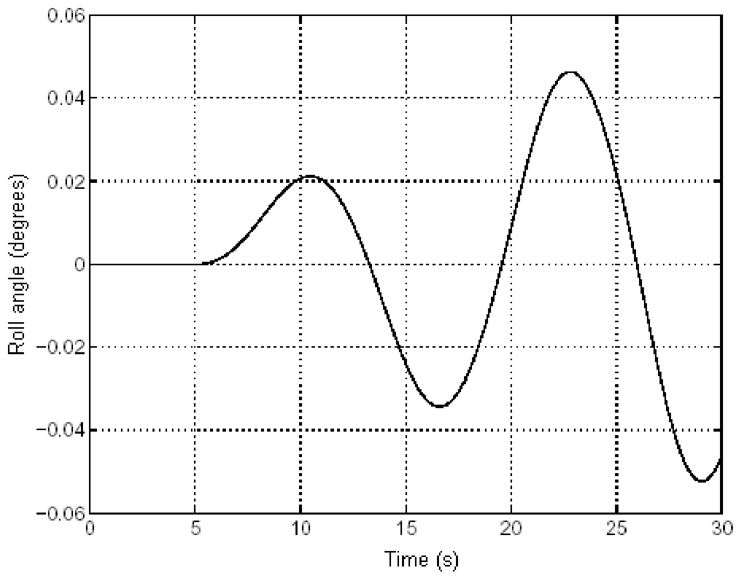

Figure 7. Combat vehicle's roll.

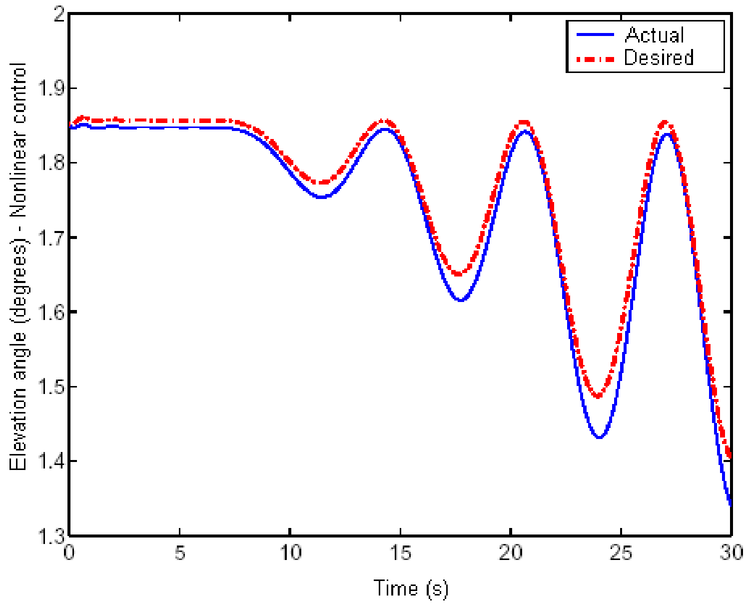

Figure 8. Nonlinear control elevation angle: actual and desired.

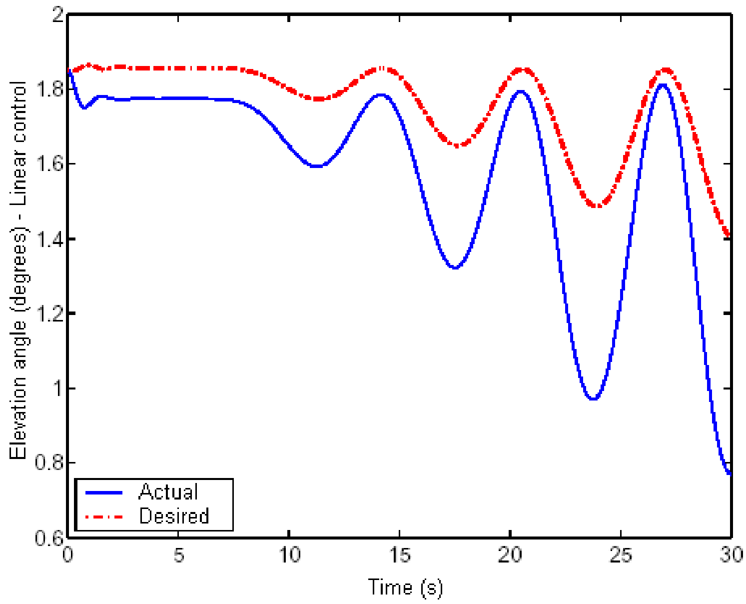

Figure 9. Linear control elevation angle: actual and desired.

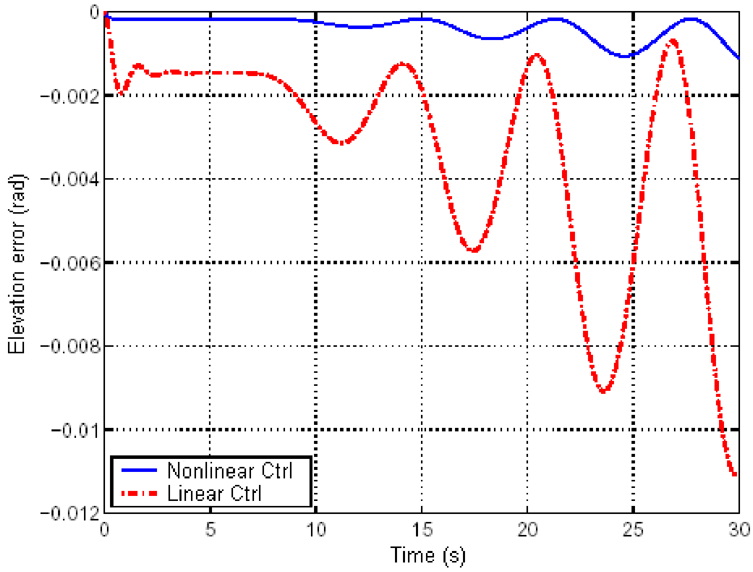

Figure 10. Elevation error: nonlinear and linear control.

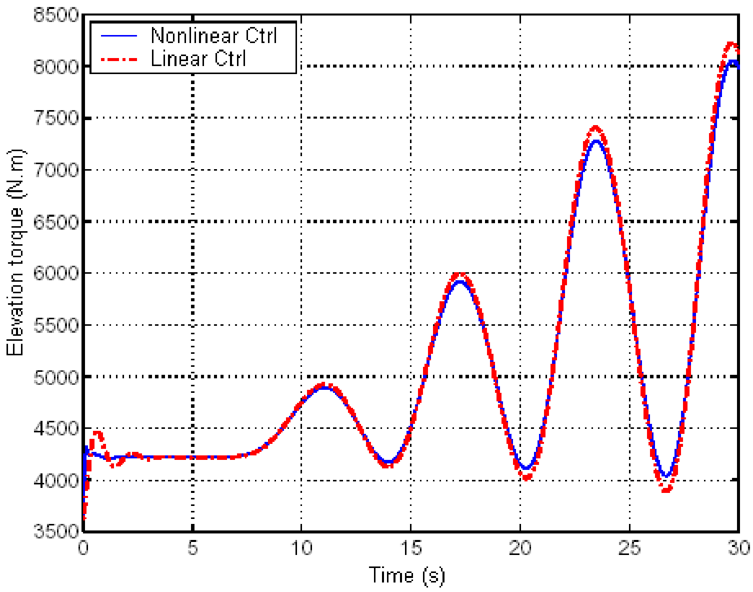

Figure 11. Elevation control torque: nonlinear and linear control.

5. Conclusion

Here, we offer a brief summary of a broad work done on gun-turret modelling and control. The overall contribution of the work is the development of a methodic approach to such problems, extensible to mobile robots in general. The main results are a realistic model of the Leopard 1A1 tank, from the gun-turret control perspective at least, and the indication that nonlinear control laws are worth pursuing for such class of system, as they may improve the precision.

6. Acknowledgements

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