Force Planning for Underground Articulated Robot

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Abstract. In this paper, force planning for underground articulated robot is studied and the governing equations of interaction between motion and soil-structure are formulated. The objective is to develop a new swerving manner in virtue of soil-structure interaction, which affects the behavior of the underground articulated robot in path tracking. The system inputs are the thrust forces on the rear and the articulation actuator. Consideration of the machine-soil interaction allows for the representation of the drift-off course due to swerving typically observed in shield tunnelling. A general force-planning model is established for path tracking of shield machine. Lastly, a simulation is adopted to show the real states during excavating.

Keywords: Shield machine, nonholonomic system, machine-soil interaction, force planning, finite element analysis.

1 Introduction

Tunnel plays an important role in traffic that has so far exhibited a slow uptake of robotics and automation technology, but this is beginning to change. Shield machines play an important role in tunneling. Closed-type shield tunneling methods were developed together with computer-aided automatic control systems[1, 2]. Many tasks performed by a robot manipulator require the robot to interact with its environment. Implementation of all these tasks intrinsically necessitates that a robot, besides realizing the predisposed position, provides the necessary force to either overcome the resistance from the environment, or comply with environment[3]. Shield machine can be considered as a kind of underground robots. And force planning involves integration of task goals like modeling the environment, position, velocity and force feedback, and adjustment of the applied torque to the robot joints. The difference between underground robots and ordinary robots mainly lies in the work circumstance. Underground robots have to interact with soil and can only move forward. Finite element analysis has been used to simulate the shield tunneling operations, shield behavior, and behavior of the ground[4]. However, in all reported work[1, 2, 4], ground is considered as a obstacle in travel. In this paper, it acts as two sides of coins, which may be a obstacle in excavating, but may be a tool in swerving. The next generation of the shield machines can be considered as a special kind of autonomous underground robots(AURs). One important question has to be answered, which is “How should I go there?”. There, however, is limited literature on force planning for AURs. Multi-segment shield machine systems is a kind of underactuated multibody systems which

C. Xiong et al. (Eds.): ICIRA 2008, Part I, LNAI 5314, pp. 64–74, 2008.

are a special instance of mechanical systems having equal input commands to the number of desired system outputs, but fewer than degrees of freedom. The main contribution of the authors is to present a method as an advanced force planning for AURs.

2 Geometric Model

A multi-segment shield machine can be found in Ref.[5]. The length of the head of the shield machine is 3.645m, and the second is 3.675m. The radius is 1.375m. Shield machine systems is an interesting example of underactuated robot which is represented by a kinematically redundant manipulator with all joints passive and forces/torques applied to the end-effector as the only available input command. From a control viewpoint, however, this kind of mechanism is similar with a manipulator with both active and passive joints[6]. Steering of this shield machine is quite different from ordinary robots: it is achieved by changing the angle between the front and rear unit. The reason for this particular structure is more capability in negotiating curves in underground. The motion mode is particularly studied for underground tunneling because there is no space for turning maneuver.

The time-depended tracking errors are determinate by measuring the position error and the orientation error between the required values and the actual values. The relations between shield machine and tunnel are shown in Fig. 1. Fig. 2 is the Sensitivity analysis of departure displacement. Based on these errors a controller is expected to set the steering angle to the appropriate magnitude to bring the vehicle to its desired path[7].

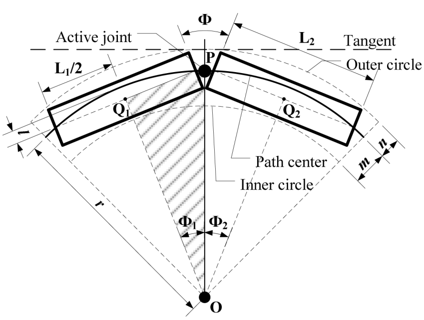

Fig. 1. Schematic of Steering of the underground robot

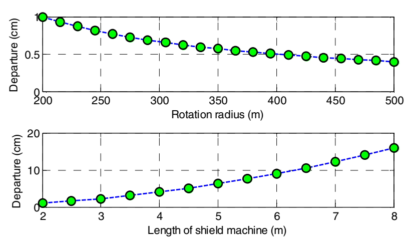

Fig. 2. Sensitivity analysis of departure displacement

The top figure in Fig.2 shows the result of a test simulation of a segment with 3.66m=(3.645m+3.675m)/2 length in curved tunnel with a radius from 200m to 500m. The bottom figure shows the result of a test simulation in 200m excavated by a segment with length of 2 to 8m. The implemented automatic steering of the individual jack thrusts leads to a deviation from the prescribed driving path of max. In order to achieve the desired driving path in the simulations more precisely, the steering algorithm for the jack thrusts should be further improved.

One of the key issues for underground automation is navigation. A review of appropriate navigation techniques is presented in Ref.[8]. Each unit is not equipped with wheels, and cannot be steerable. This is performed through changing the angle between the front and rear unites. In practice, this is normally done by controlling the length of a hydraulic cylinder between the two units. It is very difficult to changing the angle in shield machines with long segments and will cost very larger power. If the angle is changed in virtue of structure-soil coupling force, it may be easier and much energy may be saved. The whole unit becomes like a rigid body, and it has a planar rigid body motion.

It is to note that at each instant a curved path can be represented by the tangent to the path at the position of interest. Point O is the centre of a circle, and the angle Φ_1 and Φ_2 can be get by

$$\begin{cases} \sin\Phi_1 = \dfrac{PQ_1}{OP} \\ \sin\Phi_2 = \dfrac{PQ_2}{OP} \end{cases} \Rightarrow \Phi = \Phi_1 + \Phi_2 \tag{1}$$

With the presence of the articulation actuator certain degree of constraint will be added to the motion of the free system. When this actuator is stationary, the effect of the torques will be transferred from one unit to the other and finally cancelled by the ground lateral reaction. When the actuator is in action, the shield machine can move such that it accommodates the relative motion between the two units. In other words, the shield machine's motion is composed of the motion as a rigid body plus the motion due to an internal force between the two units[7].

Shield machine is a typical underground robot, and its movement is very similar to the multi-link manipulators. Usually, the motion control of an underactuated manipulator can be realized on dynamic level only, and the motion of the passive joint is controlled by the actuated joint indirectly. The controllability of the underactuated manipulator depends on the dynamic coupling between the actuated joint and the passive one.

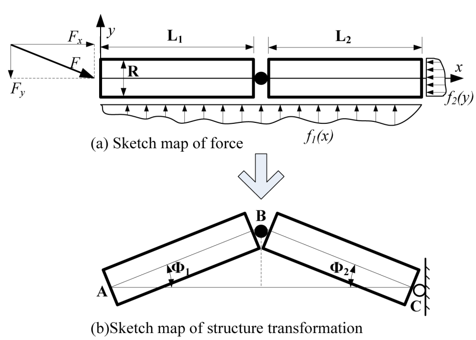

Fig. 3. The relation between the force and the structure transformation

In shield machine system such as Fig.3, however, the movement is very slow so as to be considered as a quasi-stationary system. The coupling relation in virtue of dynamics disappears in shield machine system. In analyzing the motion of low-speed robot the inertial forces can be often neglected, and the studies on kinematics and mechanics play more important roles in AURs than dynamics. This would be attractive in particular for design of controllers and similar purposes. If needed, the effect of dynamics of the steering mechanism can later be added to the formulation for simulations studies or fine tuning of a controller. At present, it is a new problem whether this shield machine is controllable, and if so, how to control this system. This problem is presented in the next section.

3 Force Model for Shield Machine Systems

3.1 Force Analysis

How to achieve a good control performance in the presence of unmodelled dynamics, sensor noise and external disturbances stimulates the needs for research on more advanced force planning algorithms. An advanced method is about to provide accurate force tracking or perfect task accomplishment in the presence of unknown parameters and uncertainties regarding the robot and environment [3].

We confine the analysis at the level of the force provided by the driving mechanism and do not consider the effects of the gear train and the losses in hydraulic actuation, etc. because of nonholonomic constraints each unit can only have a rectilinear motion along its longitudinal axis and a rotation about its mid-axle point. The motion of the shield machine system is always governed by the equilibrium of the forces acting on the system, including the ground reaction forces. In the manipulator dynamics, that the underactuated system is able to be control to the trajectory mainly lie on the initial field which, however, may be negelected in the shield machine system. How to control this kind of underactuated system is challenge problem.

Firstly, the simplified model should be established to study the coupling relation between the shield machine system and the soil. Based on this model, the force acting on the shield machine system can be given in formalism. We are to establish a mathematical model for shield machine systems. A shield machine system during excavating, there exist three kinds of kinematic states which are respectively swerve, progress and rolling. In the trajectory tracking, the rolling usually have no effect, and only swerve and progress decide the kinematic trajectory.

The most difficult case is mechanical systems with passive joints that are not subject to potential field. Potential energy plays an important role in the controllability of the nonholnomic system. For example, the underactuated multi-link manipulators is usually controlled by virtue of inertia potential energy. In this work, the soil-machine interaction is considered as a special kind of potential energy, by which the nonholonomic shield machine becomes controllable. In order to reduce the difficulty, we may take the soil-action into account as a kind of potential energy. Consider an n-degree-of-freedom mechanical system whose generalized coordinates are $q = [\, q_1 \cdots q_n]^T$, and which is enforced, in addition to the applied forces, by $m < n$

actuator forces with the control inputs $u=[u_1 \cdots u_m]^T$ affecting linearly the system dynamics. Due to the limitation of the geometric structure of the shield machine, the moving trajectory is subjected to the constraint of the minimum swerving radius,

$$\rho > R_{\min} \tag{2}$$

The shield behavior is represented by the movement of the shield in the x, y, and z directions (Δx , Δy and Δz), and the shield postures (yawing angle Φ_y , pitching angle Φ_p , and rolling angle Φ_r). The shield behavior during excavation can be obtained by solving the following equilibrium conditions of forces and moments[1] $\sum_{i=1}^{5} F_i^M = 0, \sum_{i=1}^{5} M_i^M = 0$.

In the paper, only planar problem is considered, so that several forces are not employed. Steering of this underground robot is performed by changing the angle between the two unites through an actuator. The role of the actuator(s) when not active is forming a rigid body from the rear and front units. The speed of operation is relatively low, which implies that path following might be formulated based only on the system kinematics.

3.2 Soil-Structure Interaction of Shield Tunnelling in Soft Soil

A numerical simulation using a finite element method was implemented in the aim of developing a procedure to predict the force induced by shield tunnelling in soft soil. Due to the fact that all components are included in the model, the effect of different parameters can be investigated not only with respect to the stresses, pore pressures and deformations of the soil, but also with respect to the shield machine movement. Taking into account the face support pressure in the excavation chamber, the weight of the shield machine and the frictional contact to the soil along the shield skin, the interaction of the shield machine with the soil, the jacks and the tunnel lining is realistically modeled[9]. To choose a constitutive model, one must verify its ability to represent the real behavior of the soil under the considered loading. Excavating a tunnel leads to a complex loading which will generate in particular a rotation of principal stresses. The interaction between tunnel and soil can be modeled by soil springs. The elastic-perfectly-plastic Mohr-Coulomb model is adopted in this study to calculate the stiffness of the soil according to shield machine. Because of the difficulties involved in formulating suitable analytical solutions, numerical methods have increasingly been applied. The finite element method is a well-recognized numerical tool to analyse geotechnical works because of its ability to take into account the heterogeneity of the ground, the non-linear behaviour of soils, the soil-structure interaction and the method of construction. Therefore this method appears to be the most accurate and realistic approach for tunnel analyses.

The yield surface F for the Mohr-Coulomb model is given by

$$F = 3 \cdot \alpha \cdot \sigma_m + \sigma_{eqv} - K \tag{3}$$

where, $\alpha = \frac{\tan\phi}{\sqrt{9+12\cdot\tan^2\phi}}$, $K = \frac{3\cdot c}{\sqrt{9+12\cdot\tan^2\phi}}$, $\sigma_m = \frac{\sigma_x+\sigma_y+\sigma_z}{3}$, $\sigma_{eqv} = \sqrt{\frac{1}{2}\cdot s_{ij}\cdot s_{ij}}$, $s_{ij} = \sigma_{ij} - \frac{\delta_{ij}\cdot\sigma_{kk}}{3}$.

These movements are the result of complex actions between the ground and the shield machines. The performance of a tunnel is greatly influenced by the excavation and support procedure, as well as by the initial and long term ground behaviour. A better understanding of these influences and proper consideration of their effects on support design and installation will lead to more efficient and economic tunnel construction. However, in Ref.[10] the model was used for the simulation of a shallow, straight-line tunnel advance in homogeneous, overconsolidated, soft, cohesive soil. The material behaviour of the soil is modeled by an elasto-plastic Cam-Clay model.

Due to simplicity and cost effectiveness, in many cases, researchers adapted the two-dimensional plane strain or axi-symmetrical approach of the tunnel transverse or longitudinal section. The continuous advance of the tunneling process is simulated here by using the two-dimensional finite element analysis that is based on the plane strain. The plane strain transverse section analysis provides us with the complete information of the short-term, as well as, the long-term soil deformation, stress and strain changes around the tunnel opening, and the surface settlements with time. In the longitudinal plane strain analysis, the simulation of the advancement of the shield tunneling will be accomplished in the following three stages: (1)Excavation; (2)Translation; (3)Remeshing. Simulation in the transverse plane strain section will be accomplished in the following five stages: (1)Initial heave/Settlement; (2)Repeat stage (1) for new dimension; (3)Unloading to close the tail gap; (4) Soil-liner interaction; (5)Long term deformations[11].

The finite element computations are performed using the general purpose finite element program COMSOL.Multiphysics. All deformations of the various components are expected to be small. Hence, the analyses are performed within the framework of the geometrically linear theory. Assuming quasi-static conditions and assuming both the soil grains and the pore water to be incompressible, the governing equations are given by the mass balance[10] $\mathbf{1}:\frac{\partial\varepsilon}{\partial t} + div\mathbf{q} = 0$ with the Neumann boundary condition $\mathbf{q}\cdot\mathbf{n} = q^*$, the momentum balance $div\boldsymbol{\sigma} + \rho g = 0$, and with the Neumann boundary condition $\boldsymbol{\sigma}\cdot\mathbf{n} = t^*$, the effective stress concept $\boldsymbol{\sigma}=\boldsymbol{\sigma}' - p_w\mathbf{1}$, and Darcy's law for the fluid flow $\mathbf{q} = \frac{\mathbf{K}}{\mu_w}\cdot(-\nabla p_w + \rho_w g)$ q, where, $\boldsymbol{\varepsilon}$ denotes the strain tensor, $\mathbf{q}$ the pore water flow, $\mathbf{n}$ the normal vector of the boundary and $\mathbf{q}^*$ the prescribed flow through the boundary. $\boldsymbol{\sigma}$ is the total stress tensor, ρ the density of the mixture, g the gravitational acceleration and t^* the traction vector. $\boldsymbol{\sigma}'$ denotes the effective stress tensor, p_w the pore water pressure, $\mathbf{K}$ the permeability tensor, μ_w the dynamic viscosity of the pore water and ρ_w the density of the pore water. Starting with the weak form of the mass balance including the Neumann boundary condition[10],

$$\int_{\Omega} \delta p_w \mathbf{1} : \frac{\partial \varepsilon}{\partial t} d\Omega - \int_{\Omega} \delta \nabla p_w \cdot \mathbf{q} d\Omega = -\int_{\Gamma_q} \delta p_w q^* d\Gamma_q \tag{4}$$

and the weak form of the momentum balance including the Neumann boundary condition

$$\int_{\Omega} \delta \boldsymbol{\varepsilon} : \boldsymbol{\sigma} d\Omega = \int_{\Omega} \delta \mathbf{u} : \rho g d\Omega + \int_{\Gamma_\sigma} \delta \mathbf{u} : \mathbf{t}^* d\Gamma_\sigma \tag{5}$$

3.3 Force Planning

Force control plays an important role in shield machine control[12]. Excavating by shield machine is a typical example where position and force control are of paramount importance because the internal force component of the push force should be controlled properly considering the force balance between the soil and shield machine. A classification of robot force control algorithms based on application of the relationship between position and applied force. Although force control has been drawing attention of researchers and engineers since the early days of robot development, successful practical applications of force control are still very few. In the future, however, the force control will be definitely needed in order to widen the application area and to increase dexterity of robotic mechanisms in industrial environment and also in non-industrial environment. As in the general case, there are three problems arising when attempting the control of underactuated robots, which are trajectory planning, trajectory tracking and set-point regulation, respectively. More about the relations between these three problem can be found in Ref.[6]. In shield machine systems, however, the trajectory tracking is more important than the two others. Due to the quasi-static motion, force planning plays an important role. The determination of control strategy that drives the underactuated system to complete the partly specified motion is a challenging problem. According to force balance, we can get

$$\int_0^{L_1+L_2} f_1(x) dx = F_y \tag{6}$$

$$\int_{\frac{R}{2}}^{-\frac{R}{2}} f_2(y) dy = F_x \tag{7}$$

where, F_x and F_y are components of forces F along x and y axes; F is the composition of forces of hydraulic pressure; $f_1(x)$ and $f_2(y)$ are the coupled force between the soil and the shield machine shown in Fig.3, which may be given by FEA software.

The potential energy and the virtual work can be written as

$$P = \int_0^{l_1} \frac{1}{2} \cdot f_1(x_1) \cdot \sin\Phi_1 \cdot x_1 dx_1 - \int_0^{l_2} \frac{1}{2} \cdot f_1(x_2) \cdot \left(\sin\Phi_1 \cdot x_1 - \sin\Phi_2 \cdot x_2\right) dx_2 \tag{8}$$

$$W = F \cdot \sin\alpha \cdot \left(\sin\Phi_1 \cdot l_1 - \sin\Phi_2 \cdot l_2\right) + F \cdot \cos\alpha \cdot \left(\left(1-\cos\Phi_1\right) \cdot l_1 + \left(1-\cos\Phi_2\right) \cdot l_2\right) \tag{9}$$

where, $f_1(x)$ may be given by FEA if the soil is considered as elastic-perfectly-plastic Mohr-Coulomb model. If the soil is considered as elastic model, the Eq.(8) can be simplified as

$$P = \int_0^{l_1} \frac{1}{2} \cdot k \cdot \left(\sin\Phi_1 \cdot x_1\right)^2 dx_1 - \int_0^{l_2} \frac{1}{2} \cdot k \cdot \left(\sin\Phi_1 \cdot x_1 - \sin\Phi_2 \cdot x_2\right)^2 dx_2 \tag{10}$$

where, k is able to be considered as generalized stiff coefficient.

According to the Lagrange equation, the following force balance equation can be given

$$\mathbf{F}(\Phi_1, \Phi_2) = 0 \tag{11}$$

This study focuses on mechanical control systems in which the number of control inputs is equal to the number of control outputs, and is smaller than the number of degrees-of-freedom. Some inadequacies have been faced in implementing a control law synthesized based on the linearized model to the real physical system. The objective of this work is to formulated the force of system so that the results can be compared with those based on motion kinematics only. In view of the real work surroundings of the shield machine, the force control will be employed. Force control combines force and torque information with positional data.

4 Numerical Simulation

4.1 Simulation Parameters

An experimental system was implemented in order to collect maximum data to develop a database aimed at evaluating modelling procedures, and to provide contractors with information concerning ground behaviour under shield advance conditions in order to determine the best shield control parameters. At first, the tunnel dimensions were fixed as shown in Table 1 of Ref.[1]. The physical and mechanical parameters of soil are listed in Table 1.

Table 1. Physical and mechanical parameters of soil

Quantity	Name	Expression	Unit
Young's modulus	E	10e6	Pa
Poisson's ratio	v	0.3	
Cohesion	c	10000	Pa
Friction angle	Φ	35	deg
Specific weight	γ	18000	N/m^3

4.2 Simulation Results

Then we can get the $\Phi_1 = 5.1531°$ and $\Phi_1 = 5.1955°$. Fig.4 shows the relation between the rotation angle and the control force. Soil is a material with a highly nonlinear stress-strain behavior. The strength can be characterized by the effective strength

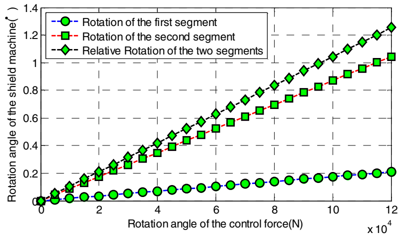

Fig. 4. The relation between the force angle and the rotation angle of the two segments

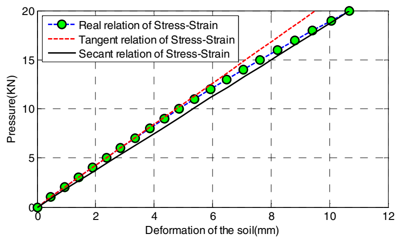

Fig. 5. The equivalent stiffness of the soil

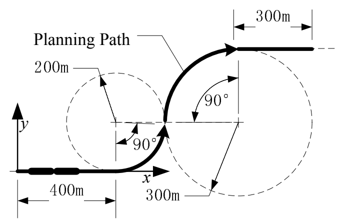

Fig. 6. The planning track

parameters c (cohesion) and ϕ (friction angle). E (Young's modulus) and υ (Poisson's ratio) describes the elastic deformation. Problems of material failure in soil mechanics and other frictional materials such as concrete are often modeled using the well-known Mohr-Coulomb law. The equivalent stiffness of the soil is shown in Fig.5. There are three different kind stiffnesses which are real relation of Stress-Strain, tangent relation of Stress-Strain and secant relation of Stress-Strain respectively. The tangent stiffness is $2.1032\times10^3 N/mm$, and the Secant stiffness is $1.8713\times10^3 N/mm$.

In order to show the mechanism of force planning presented in this paper, the track like Fig. 6 is adopted for simulation.

According to the shield machine here and the planning path, the following kinematic equation,

$$\begin{cases} P^B = R_B^C P^{B_0} + P^C \\ P^A = R_A^B P^{A_0} + P^B \end{cases} \Rightarrow \begin{cases} P^B = R_B^C P^{B_0} + P^C \\ P^A = R_A^B P^{A_0} + R_B^C P^{B_0} + P^C \end{cases} \quad (12)$$

where, P^A, P^B and P^C are the position of A, B and C in global coordination, and P^{A_0}, P^{B_0} and P^{C_0} are the position of A, B and C in local coordination.

The total length of the track is 400m+314m+ 471m+300m=1485m. When the radius is 200m, the angle is 1.0486°, and when the radius is 300m, the angle is 0.6990°. Supposed that the velocity is 1m/h. the Then we can get the corresponding force planning. The track of Points A and B is given in Fig. 7 and Fig. 8, and the latter is local results of the former. It can be noted that the two points superpose by and large except

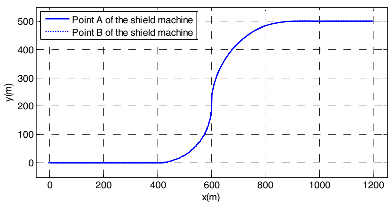

Fig. 7. Track of Points A and B

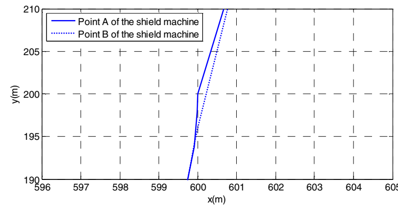

Fig. 8. Zooming in track of Points A and B

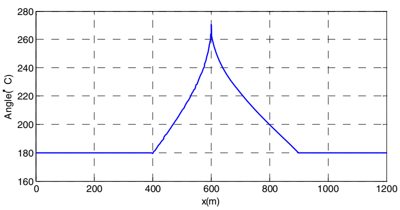

Fig. 9. The direction of Point B relative to Point A

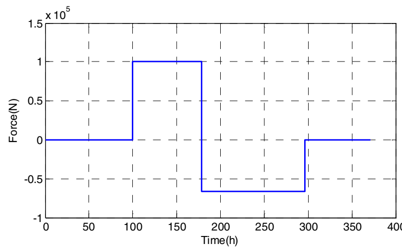

Fig. 10. Force planning

the swerve points, such as Fig. 8. The direction of Point B relative to Point A is shown in Fig. 9. The results of force planning is given in Fig. 10.

5 Conclusions

Force planning for underground articulated robot has been studied. A new swerving manner is established in virtue of soil-structure interaction. A general force-planning model is established for path tracking of shield machine. The simulation showed the real states during during excavating, and the efficiency of the method. Studies on nonholonomic underground robots will be given in the authors' coming paper.

Acknowledgment

The authors are grateful for supports from the National Natural Science Foundation of China (50705035 and 50625516), the National Fundamental Research Program of China (973) (2007CB714000) and China Postdoctoral Science Foundation (20070410276).

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