CONTROL OF REMOTELY OPERATED UNDERWATER VEHICLE USING MODEL PREDICTIVE CONTROL

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SUMMARY

This paper focuses on application of model predictive control on attitude control of remotely operated underwater vehicle. These vehicles are used in scientific, defence and oceanography applications. Remotely Operated Vehicle (ROV) considered in this paper is nonlinear model and complex. MPC is applied on ROV model to track in desired set point trajectories in the presence of uncertainties. Simulation has been carried out in MATLAB environment. Model Predictive Control has given significantly good results compared to PID, Adaptive and Variable structure control.

1. INTRODUCTION

Marine robots helps human to understand ocean in a new ways. Important advances in marine robots are improved efficiency, low cost and reduce the risks in marine operations. Marine robots play an important role in scientific, industry and military operations. It often finds solutions that may not do through other conventional methods (Lynch and Ellery, 2014).

ROV's and AUV's are considered as Marine robotic vehicles. ROV's generally used tethers to move into the ocean. But tethers have constraints on vehicle operations. It has the capability of transmitting sensor data and high quality video images up to the control at surface from the bottom of the ocean. Cables and winches are required to support the vehicle. ROV's use combination of hydraulic and electric cables for handling high power applications (Demarco, West & Howard, 2013; Corradini, Monteriù, & Orlando, 2011).

Designing a controller for Remotely Underwater vehicle is a challenging task due to complex model. Other external disturbances like ocean currents, ocean winds, forces due to umbilical cable cause additional difficulties in the performance of control systems. The kinematics and dynamics plays an important role in modeling and control of any marine robotic vehicle. This paper mainly focuses on modeling and control aspects associated with ROV (Fossen, 1994).

The main contribution of the paper is the application of model predictive control on ROV to stabilize and to control the position and orientation. Remotely Operated Underwater Vehicle model is considered from (Dyda, et al, 2015) and model is tested up to 10 % uncertainty using adaptive variable structure control. Model Predictive Control has been applied to improve the trajectory response in the presence of 15 % uncertainty. The transient and steady state response are better than Adaptive and PID controller (Dyda, et al, 2015).

Number of control techniques have been applied on ROV to control and stabilize. Simple control to complex control has been applied in literature. PID control technique has been applied for steering, diving and speed control of ROV (Dyda, et al, 2015; Caccia, et al, 2008). Sometimes it is difficult to control the overall model (six degrees of freedom) of the system so control can easily applied o decoupled model. These techniques have been used in (Isa & Arshad, 2013; Corradini, Monteriù, & Orlando, 2011). Robust controller has been applied on ROVs in (Kim, Mohan & Kim, 2014; Rau & Schroder, 2002). A H-infinity controller was applied on ROVs in (Jaulin & Bars, 2012). Sliding mode controller has been introduced to control the non-linear model of AUV (Bessa, Dutra & Kreuzer, 2010 & 2008; Cao & Ren, 2012). Adaptive control technique has been used for trajectory control of ROV in (Dyda, et al, 2015; Zhao, et al, 2014). Formation control has been introduced in ROV (Sohn, Lee & Ha, 2006; Clement, 2012). Back stepping control has also been used for terrain following. Soft computing techniques like fuzzy logic, neural network control and Genetic Algorithm has been applied for control of underwater robot thrust (Bessa, Dutra & Kreuzer, 2010; Humphris, 2010). Hybrid control techniques sliding mode fuzzy control, robust H-infinity control has also been attempted to control depth and speed of ROV (Yuh, 1990; Falkenberg, Gregersen & Blanke, 2014). Model Predictive Control is the effective control for handling constraints, multivariable and coupled systems.

2. MODELING OF AN ROV

Mathematical model of Remotely Operated Underwater Vehicle has been considered for analysing the position and orientation set point tracking (Dyda, et al, 2015; Steenson, et al, 2014). This model is unstable, nonlinear multivariable and coupled system. In order to handle all these complexities, model predictive control has chosen to track the vehicle in desired path. Finite value of Uncertainties has also been considered in this paper. Model Predictive Control is giving satisfactory response even for more values of uncertainties when compared with adaptive variable structure controller.

The ROV model has six degrees of freedom. The vehicle model is considered in inertial frame. The variables associated in horizontal plane for control purpose are surge (x), sway(y), heave (z), roll (ψ), pitch (θ) and yaw (ϕ). The ROV model is described by a set of following differential equations

$$p_1\ddot{x} + (p_2|\cos(\phi)| + p_3|\sin(\phi)|)V_x|V| + p_4x - p_5V_{cx}|V_c| = T_x \quad (1)$$

$$p_1\ddot{y} + (p_2|\sin(\phi)| + p_3|\cos(\phi)|)V_y|V| + p_4y - p_5V_{cy}|V_c| = T_y \quad (2)$$

$$p_6\ddot{\phi} + p_7\dot{\phi}|\dot{\phi}| + p_8|V_c|^2\sin(\frac{\phi-\phi_c}{2}) + p_9 = M_z \quad (3)$$

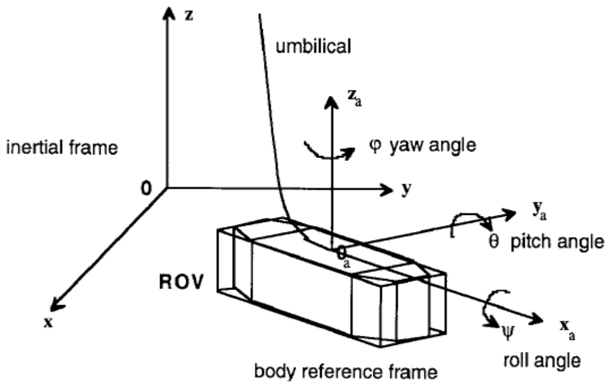

Figure.1 Operational Configuration of Remotely Operated Vehicle (Dyda, et al, 2015)

Mathematical expressions of the model parameters are as given in table-I (Dyda, et al, 2015).

Table 1.

$p_1=M+m$	$p_2=\frac{1}{2}\rho_w C_{d1}C_{r1}S_1$	$p_3=\frac{1}{2}\rho_w C_{d1}C_{r1}S_1$
$p_4=W/[\log(1+\frac{WL}{T_v})]$	$p_5=(p_4L+T_v)\rho_w C_{dc}\frac{D_c}{2W}$	$p_6=I_z+i_z$
$p_7=\frac{1}{2}\rho_w C_d C_r S r^3$	$p_8=\frac{1}{2}\rho_w[C_{d1}C_{r1}-C_{d2}C_{r2}]d_1d_2d_3$	$p_9=M_c$

where 'M' and 'm' are the mass and added mass of the vehicle, resistance moment of the cable, M_c, cable length is denoted as 'L', weight of the vehicle in the water is T_v, the weight for cable length is 'W', water density, ρ_w, drag coefficient of the cable is C_{dc}, drag coefficient of i[th] side wall (i=1,2) is C_{di} , coefficient of packing of the i-th side wall (i=1,2) is C_{ri}, equivalent area of rotation is S_i, equivalent arm of action is r, and d_i(i=1,2,3) are the dimensions of the vehicle along the x_a, y_a, z_a axes, $V_c=[V_{cx}\ V_{cy}]^T$ is the subsea current velocity, $V=[V_x\ V_y]^T = [(\dot{x} - V_{cx})(\dot{y} - V_{cy})]^T$, ϕ is the yaw angle, and ϕ_c is the angle between the x axis and the velocity direction of the current. Coefficient expressions a_i (i=1,2…9) are given in Table 1.

The thrust and torque quantities, T_x, T_y, and M_z provided by four propellers in vehicle. The mathematical expressions for inputs are given as

$$T_x = \cos(\phi)T_{xa} - \sin(\phi)\,T_{ya}$$
$$T_y = \sin(\phi)T_{xa} - \cos(\phi)\,T_{ya}$$
$$M_z = M_{za}$$

The four propeller positions are as follows

$$T_{xa} = (T_1 + T_2 + T_3 + T_4)\cos(\alpha)$$
$$T_{ya} = (-T_1 - T_2 + T_3 + T_4)\sin(\alpha)$$
$$M_{za} = (-T_1 + T_2 - T_3 + T_4)d_a$$

Where $\alpha = \frac{\pi}{4}$, $d_a = (d_x\sin(\alpha) + d_y\cos(\alpha))$

2.1 MODELING OF ROV THRUSTER

Four electric motors are used in driving the propellers of ROV. The torque force 'Q' and thrust force 'T' developed by each thruster is described (Dyda, et al, 2015) by

$$T = C_T(\sigma)\frac{\rho}{8}[V_\omega^2 + (0.7\,\pi nD)^2]\,\pi D^2\omega \quad (4)$$

$$Q = C_Q(\sigma)\frac{\rho}{8}[V_\omega^2 + (0.7\,\pi nD)^2]\,\pi D^3 \quad (5)$$

where C_T and C_Q are coefficients, functions of the angle of advance of the thruster, obtained from hydrodynamic characteristic curves of the thrusters. 'V_ω' is the speed at which water is directed for the propeller, 'D' is the propeller diameter, 'n' is the number of revolutions per second of the propeller. 'σ' is the angle of advance of propeller. Considering the speed of water entering the propeller is equal to the velocity component parallel to the line of action of the propeller, then $\sigma = 0$; with

$$\sigma = \tan^{-1}(\frac{V_\omega}{0.7n\pi nD})$$
$$T = C_T(0)\,\frac{\rho}{8}\,(0.7)^2|n|n\pi^3D^4$$
$$Q == C_Q(0)\frac{\rho}{8}(0.7)^2|n|n\pi^3D^5$$

Assuming DC motor is used in underwater propulsion. The combined dynamics of electrically driven circuit and shaft of the propeller are represented (Dyda, et al, 2015) as

$$J_m\frac{dn}{dt} + K_n n + Q = Ki \quad (6)$$

$$L\frac{di}{dt} + Ri + Kn = u_e \quad (7)$$

where the moment of inertia is denoted by J_m, revolution of propeller is n, the damping coefficient is denoted by K_n, coefficient of conversion is K, electrical current, I, armature inductance, L, resistance, R, applied voltage, u_e.

2.2 DYNAMIC MODEL OF ROV

Considering state and input vector as $z_1 = x$, $z_2 = y$, $z_3 = \phi$, $z_4 = \dot{x}$, $z_5 = \dot{y}$, $z_6 = \dot{\phi}$
$u = [T_x, T_y, M_z]^T$

The nonlinear model of ROV described by a set of equations (1-3) can be represented in state model as the combination of linear and nonlinear part

$$\dot{z} = Az + Bu + h(z) \quad (8)$$
$$y = Cz$$

where
$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{-a_4}{a_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-a_4}{a_1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \quad B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{a_1} & 0 & 0 \\ 0 & \frac{1}{a_1} & 0 \\ 0 & 0 & \frac{1}{a_6} \end{bmatrix};$$

$C = I_6$;

and

$h(z) = [0\ 0\ 0\ h_4(z)\ \ h_5(z)\ \ h_6(z)]^T$

$$h_4(z) = -\frac{1}{p_1}[(p_2|c_3| + p_3|s_3|)V_x|V| - p_5 V_{cx}|V_C|]$$

$$h_5(z) = -\frac{1}{p_1}[(p_2|s_3| + p_3|c_3|)V_y|V| - p_5 V_{cy}|V_C|]$$

$$h_6(z) = -\frac{1}{p_6}[(p_7 z_6|z_6| + p_8|V_c|^2 \sin(\frac{(p_3-\phi_C)}{2}) + p_9]$$

where $V_x = z_4 - V_{cx}$, $V_y = z_5 - V_{cy}$,

$V = \sqrt{V_x^2 + V_y^2}$,

$c_3 = \cos(z_3)$;

$s_3 = \sin(z_3)$ and I is the identity matrix

3. MODEL PREDICTIVE CONTROL

The potential of MPC are 1) it can handle constraints very effectively 2) it has optimizer which is used to optimize the control law 3) it is well suited for multivariable and interacting systems 4) It can be used for both linear and nonlinear systems 5) it can be used for both stable systems and unstable systems. One of the limitation of MPC is sometimes it may not give guarantee on stability (Corradini & Orlando, 2014).

Block diagram of Model Predictive Controller is given in Figure 2. In conventional feedback control, error signal can be computed using the difference between set point and controlled variable, whereas in MPC, the error signal is calculated using the deviation between set point future trajectory and the controlled variable prediction trajectory.

The error signal is vector value in MPC. The vector represents from current state to future state (Wang, 2010; Steenson, et al, 2014).

The important variables associated to any system are manipulated variables, controlled variables and disturbance variables. MPC has mainly three components (Rau & Schroder, 2002; Steenson, et al, 2014):

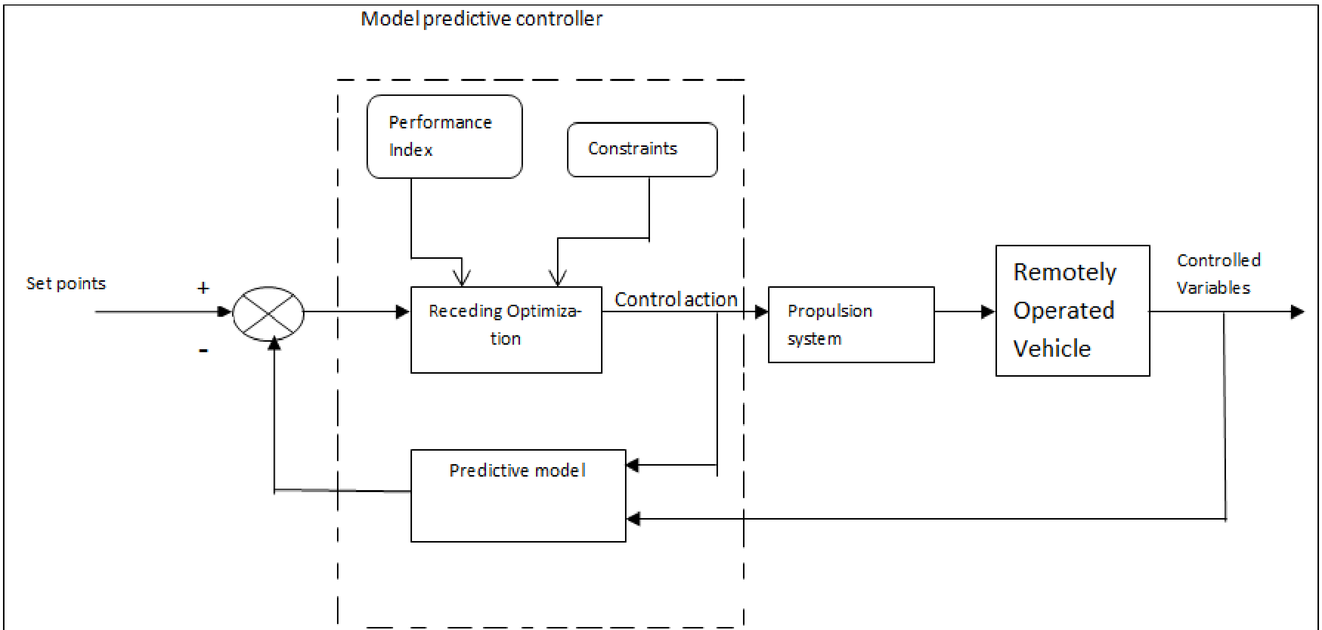

Fig.2 Block diagram of Model Predictive Control for ROV

1) A system model that predicts the system output in the future up to prediction horizon (typically, 120 or more scans)
2) The number of scans are equal in set point trajectory and predicted system output trajectory
3) The main idea of computing the control algorithm is the error between the set point trajectories and the prediction system output

Model plays a crucial role in MPC. Consider a MIMO system which is described by a nonlinear discrete time state model (Rau & Schroder, 2002).

$$x(k+1) = Ax(k)+B\Delta u(k)+K\mathcal{NL}(y(k)) \quad (9)$$
$$y(k) = C^T x(k)+D\Delta u(k)$$

where A, B, C, D are matrices of system. The vector 'K' describes the coupling of nonlinearity into the system. Δu is the increment of the input signal between two sampling instants with constraints. This model formulation is well suited for this Remotely Operated Vehicle because other MPC formulation is not suitable for nonlinear and unstable systems. In this system, linear portion is dominating the nonlinear portion. So, the following cost function and control law is proposed here.

The cost function is defined as

$$\min_{\Delta u} \sum_{i=1}^{P} \gamma^2 [r(k+i) - y^{pred}(k+i)]^2 + \sum_{j=1}^{M} \lambda^2 [\Delta u(k+j-1)]^2 \quad (10)$$

where $'\gamma'$ is the weight on the output error
'λ' is the weight on the change in input
'r' is the set point, 'u' is the input and 'y' is output

The higher λ is chosen, the slower will be the resulting controller. In order to minimize the cost function, future system outputs are required. A j-step ahead predictor is analysed by equation (10).

The control law based on least square solution in the form of Dynamic Matrix Control is

$$\Delta u = K_{mpc}\varepsilon(k+p) \quad (11)$$

Where $K_{mpc} = (A^T\Gamma^\Gamma\Gamma A + \Lambda^T\Lambda)^{-1}A^T\Gamma^\Gamma\Gamma(r - \bar{y} - d)$
ε(k+p) is the error vector

The performance and stability of system depends on M, P, Λ, Γ. Λ and Γ are diagonal matrices having the weights λ and γ. Stability of the system can be achieved by increasing Λ and P and reducing the value of M relative to P. Most of the simulation studies, performance of the system is improved with the help of Λ, Γ and M while keeping P constant. M and P are control and prediction horizons. Proof of guarantee on stability using MPC has been taken from (Chatterjee & Lygeros, 2015).

Model plays a key role in Model Predictive Control for prediction of output over a horizon. This data is used for the construction of cost function in controller design. Optimization is also possible in model predictive control. In this work, quadratic optimization is used. An algorithm is developed in this work for prediction of sequences of sampling periods (Corradini, Monteriù & Orlando, 2010).

3.1 DESIGN PARAMETERS OF MPC (Romagnoli & Palazoglu, 2006)

Some of the important design parameters of MPC are as follows:

M is the control horizon, P is the prediction horizon, Δt is the sampling period, N is the model horizon, Q and R are the weighting matrices on prediction errors and control moves.

3.1 (a) Selection of MPC parameters

1. Δt and N
The product of these two parameters should be selected such that NΔt≥ openloop settling time. The standard value of N lies between 30 and 120.

2. Prediction Horizon, P
The control action depends on P. The selection of P is equal to N+M. M is control horizon. Higher the value of P leads to poor aggressive control action

3. Control Horizon, M
The typical values of M are 5 < M < 20 or N/3 < M < N/2.Higher values of M leads to improved control action

4. Weighting matrices γ and λ
'γ' is the output weighting matrix and high values can be given to important variables. 'λ' is the input weighting matrix. Increasing the values of weights tends to make the MPC controller more conservative by reducing the magnitudes of the input moves

This paper concentrates on set point tracking of position and velocity control of remotely underwater vehicle. Here constraints are considered on input only. Based on simulation parameters and its values the vehicle is travelling as per the set point. Simulation has been developed in MATLAB environment. Parameters used in simulation are given in Table 2.

The algorithm used in proposed model predictive calculations
1. Control variables (Output), Manipulated variables and Disturbance variables should be chosen based on system model.
2. Evaluate model predictions using equation number (9)
3. Calculate control structure/law using K_{mpc}

4. Checking errors
5. Set points calculations
6. Perform control calculations using equation number (10) and (11)
7. Manipulated variables send to the ROV to get desired response

Table 2

Simulation Parameters	Value
Original Position /m	[0, 0]
Desired Position /m	[20, 20]
Desired Speed /m-sec	[10, 10]
Desired Heading /degree	120
Sampling time /s	0.2
Time /s	10
Control horizon	5
Prediction Horizon	50
Force constraint in x-direction /kN	1
Force constraint in y-direction /kN	1
Moment constraint /kN-m	1

3.2 SIMULATION RESULTS

Figure.3 represents the set point trajectories of ROV states with respect to step signal in the presence of ocean currents

Figures. 4, 5, 6 represents the reference set point trajectories for position in x, y direction and heading direction

Figure.3 represents the vehicle states following step trajectory. States x (m), y(m), ϕ (deg), $\frac{dx}{dt}$ (m/s), $\frac{dy}{dt}$ (m/s), $\frac{d\varphi}{dt}$ (deg/s) are considered on y-axis and time (s) are taken on x-axis.

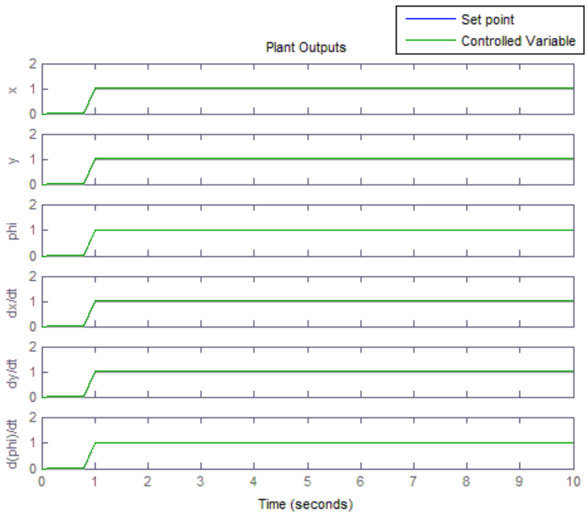

Figure.3 Set point trajectory of underwater vehicle states subjected to step input

Set point is taken as 20 m in x-direction. ROV is tracking along the set point.

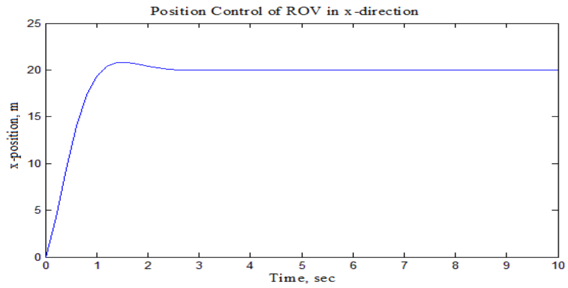

Figure.4 position control of ROV in x-direction

Set point is taken as 10 m in y-direction. ROV is tracking along the set point.

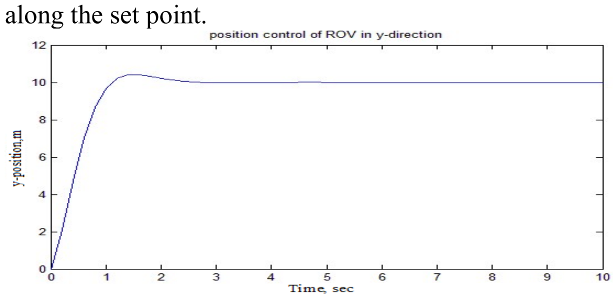

Figure.5 position control of ROV in y-direction

Figure 6 represents ROV in yaw angle of ROV and set point is taken as 120 degrees depth.

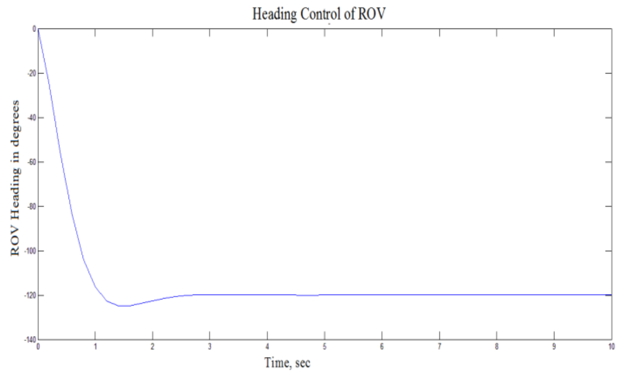

Figure.6 ROV Heading

4. CONCLUSIONS

The desired attitude control of remotely operated vehicle has been maintained at their set points with the proposed model predictive control. ROV is unstable, nonlinear, multivariable and coupled system. In general MPC may not give guarantee on stability. The MPC formulation used in this paper stabilizes the ROV without using output feedback or state feedback technique. The desired path of the vehicle tracking is controlled and effective. It is observed through MATLAB software. The results shows vehicle is following set points in the presence of disturbances when compared with PID and adaptive control techniques.

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