Abstract—In this paper, a sampled-data model predictive tracking control method is presented for mobile robots which is modeled as constrained continuous-time linear parameter varying (LPV) systems. The presented sampled-data predictive controller is designed by linear matrix inequality approach. Based on the input delay approach, a controller design condition is derived by constructing a new Lyapunov function. Finally, a numerical example is given to demonstrate the effectiveness of the presented method.

Keywords—Model predictive control, sampled-data control, linear parameter varying systems, LPV.

I. INTRODUCTION

MOBILE robots nowadays move autonomously by recognizing external environment and determining the situation through the remote control. With the development of network communication, implementation employing wireless & wired network is widespread [1]. Though control through network is advantageous in maintenance, installation, flexibility and cost, it has to be carefully designed in reality. It may cause instability and performance degradation without considering network induced delay or data packet losses. Therefore, the design of control scheme should consider with aspects and performances of whole systems.

Model predictive control (MPC) scheme is very useful since it provides good tracking performance and the MPC tuning parameters are explicitly related to the key characteristics safety, comfort, and fuel economy. But if the model is not accurate, the control technique does not guarantee the stability and performance [2]. Also, an important issue in the implementation of MPC algorithm is the discretization. A continuous-time model is much more natural and accurate in terms of describing the behavior of a system. Also, in network control systems, choosing proper sampling interval is very important for designing suitable controllers. It is clear that a longer sampling period will lead to lower communication channel occupation, few actuation of the controller, and less signal transmission. Thus, it is very important to consider the stabilizing control design problem under a bigger sampling period [5]. For sampled-data systems, the input delay approach has been widely used [4], which is based on the representation of the sampled-data system as a continuous-time system with a delayed control input. Then, the Lyapunov Krasovskii functional (LKF) method can be used to establish the stability conditions. Recently, based on the input delay approach, the sampled-data control problem of dynamical systems with time-varying delay has been investigated in [3], [4].

In this paper, we consider a continuous-time LPV model to handle mobile robot systems and present a model predictive control method for the systems with sampled-data. To the best of authors’ knowledge, there are no approaches considering sampled-data MPC for mobile robots. The presented synthesis condition is formulated by construction of a suitable Lyapunov-Krasovskii’s functional and control inputs are obtained by minimizing the upper bound of the cost function satisfying the cost monotonicity. Finally, we demonstrate the effectiveness of the proposed approach via numerical simulation.

II. DESCRIPTION OF MOBILE ROBOT

The dynamics of mobile robot with a rigid body and wheels can be described as follows [1]

\[
\begin{align*}
\dot{x} &= v \cos(\theta(t)), \\
\dot{y} &= v \sin(\theta(t)), \\
\dot{\theta} &= w(t)
\end{align*}
\]  

where \([x, y, \theta]\) denotes the position and orientation of the center with respect to a global frame, \(v\) is the translational velocity, and \(w\) is the angular velocity.

For the given mobile robot, the reference trajectory is set to

\[
\begin{align*}
\dot{x}_r(t) &= v_r(t) \cos(\theta_r(t)), \\
\dot{y}_r(t) &= v_r(t) \sin(\theta_r(t)), \\
\dot{\theta}_r(t) &= \omega_r(t)
\end{align*}
\]  

W. Kwon is with the Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang, Kyungbuk, 37673, Republic of Korea (e-mail: ckaist@postech.ac.kr).

S. M. Lee is with Department of Electronic Engineering, Kyungpook National University, Daegu 41566, Republic of Korea (e-mail: moony@knu.ac.kr).

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2014R1A1A4A01003860).
where \( x_r, y_r, \theta_r \) are references in Cartesian coordinate, \( v_r \) is the reference translational velocity, and \( \omega_r \) is the reference angular velocity. Considering local coordinate frame, define
\[
\begin{bmatrix}
  x_c(t) \\
  y_c(t) \\
  \theta_c(t)
\end{bmatrix} =
\begin{bmatrix}
  \cos(\theta(t)) & \sin(\theta(t)) & 0 \\
  -\sin(\theta(t)) & \cos(\theta(t)) & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x_r(t) - x(t) \\
  y_r(t) - y(t) \\
  \theta_r - \theta(t)
\end{bmatrix}.
\] (3)

From (1)-(3), the error dynamics is obtained as
\[
\begin{cases}
  \dot{x}_e(t) = \omega(t)y_e(t) + v_r\cos(\theta_e(t)) - v(t), \\
  \dot{y}_e(t) = -\omega(t)x_e(t) + v_r\sin(\theta_e(t)), \\
  \dot{\theta}_e(t) = \omega_r - \omega(t),
\end{cases}
\] (4)

In general, systems represented by nonlinear systems can be transformed into Linear Parameter Varying (LPV) systems
\[
\dot{X}(t) = A(\bar{v}(t), \bar{\omega}(t), v_r(t))X(t) + BU(t),
\]
where \( A(\cdot) \) is system matrices containing a time varying parameter \( \bar{v}, \bar{\omega}, v_r \), \( X = [x_c, y_c, \theta_c] \), and \( U = [v - \bar{v}, \omega - \bar{\omega}] \). By computing Jacobian matrix, the system matrices are given as
\[
A(\bar{v}(t), \bar{\omega}(t), v_r(t)) =
\begin{bmatrix}
  0 & \bar{\omega}(t) & 0 \\
  -\bar{\omega}(t) & 0 & v_r(t) \\
  0 & 0 & 0
\end{bmatrix},
B =
\begin{bmatrix}
  1 \\
  0 \\
  0
\end{bmatrix}.
\]

For a given sampling rates, the matrix \( A(\bar{v}(t), \bar{\omega}(t), v_r(t)) \) is subject to a polytope set \( \Omega \).
\[
A(\bar{v}(t), \bar{\omega}(t), v_r(t)) = \sum_{i=0}^{L} \lambda_i A_i,
\]
where \( \Omega = \{A_1, A_2, \ldots, A_L\} \) is the convex hull.

In the typical system architecture, control signals are conveyed through network communication. In network environments, the control signals pass through zero-order-hold (ZOH) which generate functions with a sequence of hold times \( 0 \leq t_0 < t_1 < \cdots < t_k \cdots \leq \lim_{k \to \infty} t_k = +\infty \). Taking consideration of ZOH, the control input is
\[
U(t) = KX(t_k),
\]
where \( K \) is the control gain matrix. Without loss of generality, it is assumed that the sampled time interval is bounded by \( h(t) \leq h_M \)

where \( h(t) = t_{k+1} - t_k \), and \( h_M \) is the maximum sampled delay. Using sampled signals, the systems are expressed as delayed LPV systems
\[
\dot{X}(t) = A(t)X(t) + BU(t - h(t)).
\] (7)

**Lemma 1.** [5] For given matrices \( A_1, A_2, \Psi \), and a scalar \( 0 \leq \tau(t) \leq \tau_M \), if the following conditions hold
\[
\tau(t)A_1 + (\tau_M - \tau(t))A_2 + \Phi < 0,
\] (8)
then, it is equivalent to
\[
\tau_M A_1 + \Phi < 0, \tau_M A_2 + \Phi < 0.
\] (9)

**Lemma 2.** [6] For given matrices \( H, N, R > 0 \) and a continuously differentiable function \( x(t) \) in \([a, b] \in \mathbb{R}^n\), the following inequality is ensured.
\[
-\int_a^b \dot{x}^T(\alpha)R\dot{x}(\alpha)ds \leq \text{Sym}\{c_1^T H e_2 + c_1^T N e_3\}
\] (10)
\[
+ (b - a)c_1^T \left( \frac{3H R^{-1}H + N R^{-1}N}{3} \right)e_1,
\]
where \( e_1 \) is any vector, \( e_2 = x(b) - x(a) \), and \( e_3 = x(b) + x(a) - \frac{1}{2} \int_a^b x(s)ds \).

**III. MAIN RESULTS**

The main purpose of this paper is to design a proper sampled-data model predictive controller. Model Predictive Control is used to approximately obtain optimal trajectories. Therefore, choosing the following performance index is reasonable:
\[
J = \int_0^\infty X^T(t)QX(t) + U^T(t)RU(t)dt
\] (12)
where \( Q, R \) are coefficients. For the given performance index, if the following condition is satisfied
\[
\dot{V}(t) + ||X(t)||^2_Q + ||U(t)||^2_R < 0.
\] (13)

With predefined Lemmas and notations, we present design methodology of model predictive control for delayed LPV systems by deriving a set of linear matrix inequality conditions.

**Theorem 1.** For a given parameter \( h_M \) and a vector \( X(t_k) \), if there exist positive matrices \( G, \tilde{P}_1 > 0, \tilde{P}_2 > 0 \), \( \begin{bmatrix} \tilde{U}_1 & \tilde{U}_2 \\ \ast & \tilde{U}_3 \end{bmatrix} > 0, \hat{V} > 0, Y, \hat{Z}_1, \hat{Z}_2 \), satisfying the following LMI conditions, the control input at time instant \( t_k \) guarantees the performance
index (12) with \( \gamma \).

\[
\begin{align*}
\min \gamma & \quad \frac{1}{1} X^T(t_k) \geq 0, \\
\sum_{i=1}^2 \gamma_i & \geq 0, \quad \text{for } i = 1, 2, \ldots, L, \\
\gamma_i & \leq 0, \quad \text{for } i = 1, 2, \ldots, L, \\
\left[ \begin{array}{c}
G^T + G - P \end{array} \right] & \geq 0
\end{align*}
\]

where

\[
\Sigma_i = \left[ \begin{array}{ccc} \Sigma_{11} & \Sigma_{12} & h_M \cdot D_1 \bar{Z}_1 \\
0 & 0 & 0 \\
-3h_M \cdot \bar{U}_1 & 0 & 0 \\
\end{array} \right]
\]

then, the state feedback gains are given as \( K = YG^{-1} \).

**Proof.** Choosing the following Lyapunov-Krasovskii functional (LKF) for \( t \in [t_k, t_{k+1}) \) yields

\[
V(x_t) = V_1(t) + V_2(t) + V_3(t)
\]

where

\[
\begin{align*}
V_1(t) &= \int_{t_k}^t X(s)ds P_1^{-1} X(t) + 2 \int_{t_k}^t X(s)ds P_2 X(t), \\
V_2(t) &= \int_{t_k}^t X^T(s)U_3 X(s)ds + 3\int_{t_k}^t X(s)ds P_2 X(t), \\
V_3(t) &= \int_{t_k}^t X^T(s)U_3 X(s)ds
\end{align*}
\]

Pre-and post-multiplying with a matrix \( \gamma^{1/2} \times \text{diag}(G, G, G, G) \), the followings are satisfied with Lemma 1.

\[
\begin{align*}
\Sigma_1 & = \Sigma_1 + h(t) \Sigma_2 + (h_M - h(t)) \Sigma_3, \\
\Sigma_2 & = e_1^T P_1 e_1 + e_2^T P_2 e_1 + e_3^T P_1 e_2 - (e_1^T U_3 e_2) - (e_2^T U_3 e_2) + (e_1^T e_2), \\
\Sigma_3 & = e_1^T U_3 e_2
\end{align*}
\]

Differentiate the LKF

\[
\begin{align*}
\dot{V}_1 &= 2X^T(t)(G^{-1} P_1 G - \dot{X}(t)) + 2 \int_{t_k}^t X(s)ds P_2 X(t), \\
\dot{V}_2 &= -\int_{t_k}^t X^T(s)U_3 X(s)ds - 2X^T(t_k)U_2 \\
&= (X(t) - X(t_k)) - h(t)X^T(t_k)U_3 X(t_k) - (h_M - h(t)) \left[ \frac{X(s)}{X(t_k)} \right] U \left[ \frac{X(s)}{X(t_k)} \right], \\
\dot{V}_3 &= \left[ \frac{X(t)}{X(t_k)} \right] V \left[ \frac{X(t)}{X(t_k)} \right] + 2h(t) \left[ \frac{X(t)}{X(t_k)} \right] V \left[ \frac{X(t)}{X(t_k)} \right] = 0.
\end{align*}
\]

From Lemma 2, the following holds

\[
\begin{align*}
\int_{t_k}^t X^T(s)_U \dot{X}(s)ds & \leq \text{Sym} \{ e_1^T Z_1 e_2 + e_2^T Z_2 e_2 \}, \\
&= \gamma R \left( \frac{3Z_1 U_{11} - Z_2 U_{22} Z_2^{-1} Z_2}{3} \right) e_1
\end{align*}
\]

where \( Z_1, Z_2 \) are auxiliary variables. Taking into account system dynamics (7),

\[
2[X^T(t)G^{-1} + \alpha X^T(t)G^{-1}][-X(t) + A_1X(t) + BKX(t)]
\]

Summing up from (20) to (24) leads to

\[
\dot{V} + X^T(t)QX(t) + U^T(t)RU(t) \leq \zeta(t) \Sigma \zeta(t)
\]

where

\[
\Sigma = \Sigma_1 + h(t) \Sigma_2 + (h_M - h(t)) \Sigma_3,
\]

then, the state feedback gains are given as \( K = YG^{-1} \).
where \( \bar{U} = GUG, \bar{V} = GV G, \bar{Z}_1 = GZ_1 G, \bar{Z}_2 = GZ_2 G \), and \( K = YG^{-1} \). Using Schur complement, The equations in (25) and (26) are equivalent to those of (16) and (17). For every sampling instance, \( V_2 \) and \( V_3 \) vanish. Then, the upper bound of LKF is expressed in terms of \( V_1 \).
\[
X^T(t_k)GP(t_k)GX(t_k) \leq \gamma, \tag{28}
\]
where \( \gamma \) denotes the bound of optimal performance index. The effect of input saturation is considered similar to the method in [7]. This ends the proof. \( \square \)

IV. NUMERICAL EXAMPLE

Example 1 This example considered the dynamical equations of the system represented from error dynamics.
\[
\dot{X}(t) = A_1 X(t) + BU(t - h(t)) \tag{29}
\]
where
\[
A_1 = \begin{bmatrix}
0 & -0.05 & 0 \\
\omega_r & 0 & v_r(t) \\
0 & 0 & 0 \\
\end{bmatrix},
\]
\[
A_2 = \begin{bmatrix}
\omega_r & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix},
\]
\[
B = \begin{bmatrix}
-1 & 0 \\
0 & 0 \\
0 & -1 \\
\end{bmatrix}.
\]
The model parameters are calculated with a sampling time 0.1s. The sampling time \( h(t) \) is less than 0.1 s. Along the reference trajectory, the input is constrained to \(-0.1 \leq u(1) \leq 0.1 \) and \(-0.05 \leq u(2) \leq 0.05 \).

The corresponding controller gain matrix is
\[
K = \begin{bmatrix}
-0.5777 & 0.3442 & 2.6729 \\
-0.2079 & 0.1255 & 0.9746 \\
\end{bmatrix}
\]
Fig. 2 shows the simulation result which is obtained with the above controller gain, taking \( Q = I \), \( R = I \), \( \alpha = 0.1 \).

V. CONCLUSION

The sampled-data MPC method for mobile robot systems have been investigated by considering constrained polytopic LPV model. Based on the input delay model, sufficient conditions for the sampled-data MPC controller design are obtained by constructing a new Lyapunov functional. The effectiveness of the presented method has been verified by illustrating numerical simulation.

REFERENCES