Abstract—Balance stability is a research hotspot in the humanoid robot field. Researchers have put forward many methods to deal with the push recovery issue. This paper firstly introduces the current mainstream balance models and stability criteria. Secondly, discusses the commonly used balance strategies and algorithms from two aspects of standing balance control, walking balance control. Finally, concludes the existing problems as well as further research challenges in the study of balance control.

Keywords: humanoid robots; standing balance; walking balance

I. INTRODUCTION

The humanoid robot is a kind of intelligent robots with the human form, which is susceptible to various disturbances and tends to imbalance while working. Push recovery is an important research direction in the humanoid robot field. However, the motion of the humanoid robot is generally characterized by high-order, multi-degree of freedom, nonlinearity, small support polygon, and strong coupling between joints, causing balance control a complicated problem.

At present, the balance control of the humanoid robot mainly includes two directions: standing balance control [22] and walking balance control [25]. In the standing state, the stability of the robot is maintained mainly through the ankle, hip and stepping strategies [11]. For smaller disturbances, the robot can maintain balance through the ankle and hip strategies [9], while for larger disturbances, mainly through the stepping strategy [10]. In the walking state, the stability of the robot includes walking trajectory design without external disturbances, balance control and trajectory recovery under disturbances. Without external disturbances, the Zero Moment Point (ZMP) trajectory of the robot is designed with reference to the ZMP trajectory of the human walking. The Center of Mass (CoM) trajectory and joint angle trajectories which control the robot to walk are obtained by using simplified models and the inverse kinematics [4]. When disturbances occur, the balance controller needs to bring the robot back to the normal walking state by imitating human reactions to external disturbances, including upper-body rotation, arm-swing, swinging leg amplitude modulation [28] etc.

The paper is organized as follows: Section II presents the commonly used simplified models and stability criteria of the balance control. Section III introduces standing balance control strategies and algorithms. Section IV introduces walking balance control strategies and algorithms. Section V discusses challenges and future developing directions in the study of the balance control. Section VI concludes the paper.

II. BALANCE MODELS & STABILITY CRITERIA

In the study of balance control schemes, simplified models are used to simulate the motion of the humanoid robot. These models treat the external interference as the disturbance to the velocity of COM. When disturbances occur, the velocity of COM becomes non-zero and COM will move under the combined effects of the external force, the ground reaction force and joint control torques. Balance control strategies are aimed at reducing the velocity of COM by designing joint control torques, making the model restore to the steady state gradually.

The commonly used simplified models include the Linear Inverted Pendulum Model [1], the Linear Inverted Pendulum Plus Flywheel Model [3], the 3D Linear Inverted Pendulum Model [2], the 3D Linear Inverted Pendulum Plus Flywheel Model [2], the Cart-Table Model [4] and the Multi-Link Model [5], as shown in Fig. 1 (a) - (f). The support polygon in Fig.1 refers to the largest convex polygon formed by all the edge contact points between the feet and the ground.

Based on different control mechanisms, the models can be divided into ankle control models and angular momentum control models. Ankle control models include the Linear Inverted Pendulum Model and the Cart-Table Model. The Linear Inverted Pendulum Model (LIPM) assumes that the mass of the body is concentrated at a point called CoM, and ground reaction forces are equivalent to the resultant force acting on a point named CoP. The two points are connected by a telescopic and massless link, as shown in Fig. 1 (a), (e). The control variable of LIPM is the COP position. The Cart-Table Model assumes that the whole mass of the body is concentrated on the cart which moves on the horizontal table of negligible quality, as shown in Fig. 1 (e). When the cart moves at an appropriate acceleration, CoP can be maintained within the support polygon and the table will be in equilibrium. The control variable of the model is the CoM acceleration rate. The above models only use the ankle torque to realize the balance control. During the control process,
the height of CoM remains constant and the angular momentum about CoM is zero. Thus, they cannot simulate the effect of upper-body inertia on the balance control. Angular momentum control models include the Linear Inverted Pendulum Plus Flywheel Model and the Multi-Link Model. The models replace the point mass by a flywheel to simulate the effect of the upper-body rotation, as shown in Fig.1 (b), (d), (f). These models use the flywheel torque to change the resultant moment about CoM, pulling the robot back to the stable state.

Based on different usage scenarios, the models can be divided into 2D models and 3D models. 2D models (Fig.1. (a), (b), (e), (f)) have the restriction that the direction of the external disturbance is sagittal direction when studying the balance control. By placing 2D models into the 3D coordinate system, as shown in Fig.1 (c), (d), the models can study the push recovery under horizontal disturbances from various directions.

Based on the distribution of the body mass, the models can be divided into single centroid models and distributed mass models. Single centroid models (Fig.1. (a)-(e)) assume that the whole mass is concentrated at a point, which differs a lot from the reality. The Multi-Link Model is one of the distributed mass models. It assumes that the humanoid robot is made up of rigid bodies connected by joints, and the mass of each part is evenly distributed on these rigid bodies, which is closer to reality than the single-centroid models, as shown in Fig.1 (f). However, the balance control algorithm of distributed mass models is more complicated, computation-intensive and time-consuming, making it difficult to achieve the desired control effect. It is necessary to improve the computation ability and develop efficient algorithms to obtain ideal control result.

In terms of stability criteria of the humanoid robot, scholars have proposed Center of Pressure (CoP) \[^6\], Zero Moment Point (ZMP) \[^6\], Foot Rotation Indicator (FRI) \[^7\], Centroidal Moment Pivot (CMP) \[^8\], Capture Point (CP) \[^9\] etc.

CoP is the point where the ground reaction force acts. When CoP lies inside the support polygon, the robot is instantaneously stable. When CoP lies on the edge of the support polygon, the robot tends to flip or has been flipped over. ZMP is the point on the ground at which the horizontal moment generated by the ground reaction force/torque equals zero. Goswami pointed out that ZMP and CoP can be regarded as the same point. ZMP stability criterion is identical to that of CoP \[^7\]. Since ZMP/CoP cannot distinguish between flipping trend and flipped state, it is necessary to ensure that ZMP/CoP has a certain safe distance from the edge of the support polygon when using the criterion.

There is no essential difference between FRI and ZMP/CoP. FRI lies on the ground, within or outside the support polygon and is the stability criterion of single-leg support phase. When FRI falls within the support polygon, it coincides with ZMP/CoP, and the robot is instantaneously stable. When FRI falls outside the support polygon, the robot is unstable. FRI can be used to distinguish between the flipping trend and flipped state of the robot, indicate the possibility of the foot rotation, calculate the unbalanced moment on the foot, get the direction of the foot flip. CMP is the point of intersection of ground and a straight line parallel to the ground reaction force, passing through the CoM. When CMP coincides with ZMP/CoP, the ground reaction force passes through CoM, which means the resultant moment about CoM is zero and the robot is instantaneously stable. Rather than vice versa. The essence of maintaining balance by upper-body rotation is to generate the moment about CoM opposite to the direction of the motion and make CMP coincide with ZMP/CoP.

In 2006, Pratt introduced Capture Point (CP) and Capture Region (CR). CP is the location where CoP should arrive to recover balance after disturbances. In the angular momentum control scheme, the computed Capture Points are different depending on the degree of the upper-body rotation. These points form the Capture Region. If CR intersects the support polygon, the robot will be instantaneously stable by modulating hip and ankle torque to make CoP and CP coincidence. If the CR and the support polygon does not intersect, the robot must take steps. The stability criterion is used to analyze the stepping strategy, and CP can be used as a reference for planning footstep locations at the beginning of stepping control.

The ZMP/CoP, FRI, and CP stability criteria can be applied to any simplified model mentioned above to realize the balance control. Considering that the CMP stability criterion measures the stability based on the rate of angular momentum about CoM, it can only be applied to angular momentum control models.

Choosing the appropriate simplified model and stability criterion is the prerequisite to study balance control schemes. Good simplified models require simple operation, convenient control, and should be similar to the dynamic characteristics of the robot to increase the robustness of control strategies. Good stability criteria not only need to indicate the current state of the robot and decide whether to take the balance strategy for push recovery, but also require reducing the restriction on the robot motion, such as ZMP/CoP stability criterion requires that the support foot must fully touch the ground, which makes a greater constraint on the design of the balance control scheme.

III. STANDING BALANCE

There are three main strategies for standing balance control: (1) Ankle Strategy. The strategy keeps CoP within the support polygon by controlling the ankle joint torque and locking all the other joints. Due to the maximum output torque of the ankle is limited, the strategy is used to resist small perturbations. 2) Hip Strategy. By modulating the CoM state through hip rotation, the robot can resist larger perturbations. 3) Stepping Strategy. As the perturbations continue to increase, the robot must take steps to avoid a fall. The above strategies are used to solve different levels of external disturbances. The aim of the balance controller is to achieve the rational cooperation between these strategies.

A. Ankle Strategy

When studying the Ankle Strategy, researchers generally select LIPM and use the CoP position as the control variable to design the balance controller. The design concept of the balance controller is to calculate the CoP reference position by taking the CoP reference position and locking all the ankle joint. The feedback information, and then design the ankle torque curve to decrease the tracking error between the actual CoP and the desired one.

Literature \[^9\] and \[^13\] use virtual model control to design the PD-based ankle torque control curve. The scheme realizes compliant control, but can result in system oscillation, causing the controller less robustness.

To enhance the robustness, \[^14\] selects the Cart-Table Model and uses the CoM state as the control variable to design the Model Predictive Control (MPC) based balance controller. In this scheme, the balance controller designs the CoM reference trajectory by taking the CoP reference position and the current
CoM state as input parameters of MPC cost function, and uses the inverse kinematics to make the robot gradually restore balance based on the designed trajectories. In [16], CP is used as the feedback parameter to design the MPC cost function. The controller guides CP to the reference position by modulating the COP position. These schemes realize compliant control and MPC based design increases the robustness of the controller.

B. Hip Strategy

When studying Hip Strategy, researchers generally select the LIPM Plus Flywheel, and use the flywheel torque, CoP position as control variables to design the balance controller. The design concept of the balance controller is to pull the COP position back to the support polygon by hip rotation, and then use Ankle Strategy to restore balance. The hip torque is generally designed by Bang- Bang control [11] [17] or optimal control [17]. Such torque control curves are not smooth, which cause system oscillation easily. [9] [13] use PD based torque curve and realize compliant control. In [12], the 3D-LIPM is selected to study Hip Strategy under horizontal disturbances from various directions.

To enhance the robustness, Researchers generally use MPC based schemes to design the balance controller, whose key is to design the proper cost function. [14] designs the upper body rotation angle reference trajectory by using the final rotation angle and the current CoM state as input parameters of MPC cost function. In the scheme, the final rotation angle of the upper body must be determined at the beginning of the control. The problem that how to design the mapping relations between the disturbance and the reference rotation angle needs further study.

In addition, Liu et al. [18] use the optimal trajectory library and local optimization control methods to realize the standing balance control. Literature [19] discussed the balance control algorithms under continuous and constant disturbance. As such schemes require the participation of trajectory library, the controller must design the trajectory library generation algorithms, which directly affects the effect of balance control.

C. Stepping Strategy

When studying Stepping Strategy, researchers generally select single centroid models or the Multi-Link Model, and use flywheel torque, CoP position, step length as control variables to design the balance controller. Single centroid models can only simulate single-leg support phase, that is, the support foot contacts with the ground while the swing leg swings in the air. The Multi-Link Model can simulate single-leg support phase as well as double-leg support phase, which describes the motion of the legs more accurately.

The design of the balance controller needs to focus on the swing time, which indicates the step speed. [2] analyzed the influence of the swing time on N-Step Strategy. The longer the swing time is, the smaller the gain of the stability range of N-step strategy is, but the energy consumption in taking N-step strategy is very large. Thus, if the swing time is too long, it is necessary to choose whether to take N-Step strategy by consuming large energy or to store energy to perform other protection measures according to hardware characteristics of the robot and the real environment. [22] pointed out that the relationship between the swing time and the energy consumption and proposed that we need to choose the most appropriate swing time for different disturbances by considering the energy consumption factor into the MPC cost function. The scheme designs Stepping Strategy based on minimal energy consumption, which is particularly important for small robots with limited energy.

To pre-plan the footstep location at the beginning of the control, [3] selects the LIPM Plus Flywheel and uses CP to design the controller. Due to the difference between the motion characteristics of the simplified model and that of the real robot is large, the robustness is poor when the calculated CP is applied to the real robot. [20] proposed a scheme based on offline learning and online learning, which calculates CP by using large number of experimental data to form a fitting curve. The scheme greatly increases the robustness of the application of the CP theory. Literature [26] uses the MPC based stepping controller to calculate the desired step position and design the CoM reference trajectory. However, the scheme does not consider the influence of upper-body rotation. Thus, it is a good suggestion to select the LIPM Plus Flywheel to design the CoM reference trajectory.

The existence of environmental errors and hardware errors is the import reason for poor robustness of the balance control. [21] designs the Disturbance Observer to filter and split the above two errors, and chooses different PI parameters to design the feedback controller. The scheme realizes Stepping Strategy by regulating the CoM reference trajectory based on quadratic program. It enhances the sensitivity for instantaneous errors and improves the robustness of the control system, which makes the design of the balance controller more reasonable.

In addition, [23] also proposed a neuro-based MRNN push recovery controller. The main task of the controller is to train the neural networks and complete the online learning task. After learning, the controller can select the corresponding neural network to design the joint reference trajectories according to different disturbances. Since the balance controller can only output gain variables in the range of [0,1] to plan the trajectories, it is necessary to improve the scheme for better results.

To sum up, the simple PD controller [9] [13] can cause the robot to oscillate near the equilibrium position, and the amplitudes rise with the increase of perturbation intensity, which requires more energy and time-consuming. The MPC based balance controller [14] [16] [22] takes the robot states in the future sampling time as the input parameters to design the control equations, making the effect of the balance better and the recovery process more natural. In addition, machine learning based controllers [20] [23] can plan the control curve according to the actual practical application environment. Which have a good effect on enhancing system robustness.

In recent years, more new ideas and solutions has been emerged in the field of standing balance. The control scheme based on trajectory library [18] [19] makes the push recovery process more stable and natural. The neuro-based MRNN push recovery controller can choose the appropriate strategy to resist disturbances, so that the cooperation between three strategies can become more efficient and reasonable. Balance control under continuous and constant disturbance and the 3D space have also made new progress [9][12], but still need to be improved.

IV. WALKING BALANCE

In the walking state, the stability of the humanoid robot includes walking trajectory design without external disturbances, balance control and trajectory recovery with disturbances. It is easier to design the walking trajectory for the robot without external disturbances. The ZMP trajectory of the walking robot is designed by referring to that of human walking.
In the actual project, due to the physical constraints of the hardware devices, the robot cannot walk strictly follow with the predefined trajectory. It is necessary to compensate the tracking error in the process of walking. In [4], the ZMP tracking error is used as the input parameter of the cost function to modulate system control variables based on the preview control, making the robot follow the predefined trajectory accurately. The strategy uses a preview control of ZMP, which is highly adaptive and makes the trajectory generation process more flexible.

The control strategy is more complex for the walking robot when the collision occurs, we need to study the recovery process as well as the reaction during the push process, after which we are able to constrain the ZMP in the safe region and maintain stability. The following paper will introduce the commonly used balance control strategies in two aspects: the strategies under external disturbances from sagittal direction and the strategies under external disturbances from planar direction.

[25] proposed a scheme to deal with the pushes from sagittal directions. This strategy implements the trajectory generator by using preview control with LIPM Plus Flywheel and constrains the ZMP in the safe region by rotating trunk and swinging leg quickly. And it uses the angular momentum generated by the rotation process to counteract the influence of disturbances, so that the robot can recover the normal walking state. Since this strategy can only resist of the pushes from sagittal directions, it should further strengthen its adaptability.

By regulating the angular momentum of the Center of Gravity (CoG), we can control the walking process, generate the walking trajectory, and maintain the balance under the external forces [7]. Based on CMP criterion and angular momentum regulation, Che-Hsuan Chan et al. [20] proposed that walking robots can keep balance under the sagittal-direction pushes by controlling the CoG angular momentum. This strategy estimates the CoG and ZMP states and makes them as the input parameters of the angular momentum regulator. Then it rotates trunk to regulate angular momentum by using CMP criterion and angular momentum regulator. Finally, it modifies the CoG trajectory, and swings leg to keep balance of the robot. Since the strategy does not apply the CMP criterion to the whole body of the robot, the control process is not strong enough.

The above two strategies only achieve a balance control process under the sagittal-direction forces, so some researchers proposed several strategies to keep balance of the walking robot under planar-direction forces.

Ren C. Luo et al. [27] proposed a push recovery strategy of walking robot under the external planar-direction pushes. The reference trajectory can be generated based on the preview control of the LIPM Plus Flywheel. During the walking process, the gyroscope sensor is used to continuously detect CoG state to determine whether there is external disturbance. Once the disturbance is detected, ZMP can be maintained in the safe region by selecting appropriate strategy with a torque optimization method. This strategy increases the robustness by using the preview control with ZMP error to compensate for the small deviation of ZMP and the PID controller to reduce the position and velocity deviation of the joints.

In [28], the push recovery strategy of the walking robot under planar forces was proposed by mimicking the human reactions. It can eliminate the angular momentum generated by external forces through rotating trunk and swinging legs. The trajectory generator uses the preview control to generate the trajectory and uses the human-like motion controller to promote the push recovery trajectory under external pushes. When the robot is walking along the pre-defined trajectory, the acceleration and jerk of COM are obtained by IMU to detect whether there is external disturbances. Once the external force is detected, it is decomposed into sagittal direction and lateral direction to be analyzed. Then the human-like motion controller will select appropriate strategy according to the direction of the force. The push recovery strategy uses the COM state estimated by Kalman filter as the feedback parameter to design the PI controller which controls COM to return to the desired trajectory after disturbing. The strategy further optimized trunk rotation and leg swinging, so that walking robots can better deal with the planar force.

In [29], the push recovery strategy based on five-mass with angular momentum model was proposed to deal with the planar-direction pushes. This strategy uses the ZMP preview control design the trajectory generator. It classifies the push-recovery process into collision process and recovery process according to the COM, ZMP states. In the collision process, the trajectory generator selects the appropriate balance strategy according to the strength and directions of the external forces, after which perturbation will be resist. In recovery process, the trajectory generator can generate the compensate trajectory to realize the trajectory recovery after disturbances. Since the five-mass with angular momentum model reduces the modeling error, the scheme is quite accurate than others.

The balance control for the walking robot is easier when there is no external force. The Preview Control can be used to generate the walking trajectory [15]. The control process is more complex when the walking robot is under external interferences. The key to maintaining balance is to eliminate the angular momentum from external forces. [25], [27] and [28] achieve the control of the angular momentum by applying flywheel torque to change the resultant moment about CoM, and ultimately make the model be balanced. [26] use the CMP criterion to regulate the angular momentum. The above four kinds of push recovery strategies are based on the LIPM, so the control process is relatively simple. While [29] use the five-mass with angular momentum model which consider the impact of the arms in the process of angular momentum regulation, so the control process is more complex and precise.

V. FURTHER RESEARCH

The research on the balance control of the humanoid robot has made a series of progress, but there still exists the following aspects which need further research:

- In aspect of designing simplified models. The current reference models are mostly single-centroid models, which are quite different from the dynamic characteristics of the actual robot. To simplify the robot model and ensure the accuracy of the control system, we need more in-depth analysis and introducing pioneering thinking.

- In aspect of designing stability criteria. The commonly used stability criterion is ZMP. Considering that ZMP is not directly related to the current CoM state, and the cost of calculating ZMP by the expensive feet six-dimensional force/torque sensor is large. Therefore, future research needs to consider other stability criteria.
In aspect of constraints on external disturbances. The current balance control research is mostly assumed that the external force is instantaneous impact force or constant continuous force. In future research, we need to weaken the constraints on external forces and deal with disturbances from all directions, various degrees and various forms.

In aspect of breaking through balance strategies. Currently, standing balance control is mainly realized by the ankle, hip, and stepping strategies. Yet the walking balance control under disturbances is mostly realized by torso-rotation, arm-swing, leg-swing, etc. Seeking new balance strategies has become a breakthrough in the future work.

In aspect of handling sudden situations. The current balance control schemes are highly dependent on specific joints, such as ankle and hip joints. It is an important security problem that how to maintain balance when some motors of the robot are broken in sudden situations.

In aspect of simulating of real environment. When the humanoid robot enters the real environment, its body must be in contact with the surrounding environment, which increases the difficulty of the robot’s control system. In the future, we can use more intelligent sensors such as binocular vision and laser scanning to perceive the external environment, which can improve the effect of the balance control and the intelligence of the robots.

VI. CONCLUSION

Push recovery is an important research direction in the humanoid robot filed. In this paper, we introduce the simplified models and stability criteria of the balance control research. We also analyze the typical control strategies of standing and walking humanoid robots in detail. Based on the above, the challenges and future development directions are discussed.

ACKNOWLEDGMENT

This work is supported by National Program on Key Basic Research Project under Grant 2013CB035906 and The Fundamental Research Funds for the Central University under Grant DUT16QY13.

REFERENCES


