Consider a cable maintenance vehicle equipped with a robotic arm, as shown in the figure below. The robotic arm is remotely operated from the operator cabin behind the arm. To make the operation easier, the robotic arm is automatically positioned relative to a target cable fixed to the pole (see the figure). A range sensor attached to the arm tip measures the relative distance between the cable and the arm tip, and the rotary actuator at the base of the robotic arm is controlled based on the range sensor signal.

Part 1

A) First, a proportional and derivative (PD) control was used for the feedback control from the range sensor at the arm tip. The PD control system turned out to be stable for a wide range of the feedback gains.

B) Next, the same PD control was applied to another robotic arm whose arm length was twice longer than the first one. The PD control system turned out to be unstable even for a small proportional gain.

C) In an attempt to understand the instability of the long robotic arm in B), a position sensor measuring the joint angle of the robotic arm was used for the feedback control of the long arm actuator. Its PD control system turned out to be stable for a wide range of feedback gains.

Build a lumped-parameter model competent to portray each of the stability and instability phenomena described above, A) – C). For the sake of simplicity, consider only one degree-of-freedom motion of the arm within a vertical plane. Also assume that the input command to the actuator is proportional to torque \( \tau \). Attempt to obtain the simplest model consisting of the minimum number of elements that can elucidate the stability problems. Define parameters needed for each model, and choose appropriate parameter values that physically make sense. Show how the stability and instability phenomena are explained with the models.

Part 2

When the vehicle with the shorter arm was anchored on a soft ground, the vehicle chassis oscillated as the robotic arm moved.

D) Despite the chassis oscillation, the arm tip motion was not oscillatory, when the feedback from the range sensor was used with appropriate PD gains.

E) Feedback from the joint angle sensor was also attempted. The arm tip motion turned out to be oscillatory, although the feedback signal, i.e. the joint angle, was not oscillatory.

Build simple lumped parameter models, and explain the above phenomena.