1. Introduction

Construction machines contribute significantly to efforts related to infrastructural development. Owing to the versatility of tasks that they can perform, their presence is ubiquitous on construction sites as can be seen in fig. 1.1. One of the most common tasks is that of excavation, which comprises of digging and subsequent moving of material. This makes it worthwhile to know the mass of the material or payload being carried by the machine at any given moment.

Figure 1.1.: Mobile construction machines in operation.

On-site, the construction machine, such as an excavator or a wheel-loader loads material in its bucket and unloads it into a dumper truck until it is full. The loaded dumper truck is then driven onto a stationary weighing scale to determine its weight. If the truck is not loaded to its full capacity, then it must be driven back to the excavation site for reloading. Conversely, if the truck is overloaded, it needs to be relieved of the extra material, since an overloaded vehicle is detrimental to driving safety and road condition. In fact, the issue of overloaded commercial vehicles damaging the road network is pertinent worldwide, reported in developing countries [Gat13] [SC18], as well as in developed ones [Wüp16]. Overloading has a further direct financial implication - highway authorities bear the right to impose heavy fines on overloaded vehicles.

It is thus sensible to have a payload estimation system at the source, i.e., on board the construction machine itself that loads the dumper truck. This would help with accurate loading of the vehicle, thus saving the associated driving cycle to the stationary scale as well as potential financial losses incurred through fines on the highway. Furthermore, logging the mass conveyed by the construction machine in each run can facilitate effective monitoring of the overall efficiency of the mining operation.

Apart from these direct applications, if the payload is available continuously while the machine is in motion, it can act as a significant input to the estimation of the dynamic stability of the construction machine. This aspect cannot be understated, since these machines must frequently operate on loose and uneven ground while transporting heavy loads, often while going through a to and fro motion. Hence, a continuous and dynamic estimation of the payload would also help contribute to better stability algorithms.

An overview of relevant research shows that the approaches used to determine payload for construction machines stem from the broader field of parameter estimation in the context of robot dynamics. Indeed, the form and function of the mechanical manipulator that characterizes construction machines can be intuitively compared to that of a classical robotic arm. This manipulator is commonly a hydraulically actuated multi-link mechanism that is connected at its one end to the machine, with the other end carrying the tool with which the machine executes tasks on the site. Payload estimation is therefore synonymous with the determination of the mass of material being transported in the bucket, or more generally, by the tool, which can assume different forms like a hook or a fork pallet among others.

There exist a variety of approaches to estimate the payload. The majority of them make use of the fact that the payload can be expressed in terms of the actuating torques at the joints, since a change in payload will result in a corresponding change in the joint torques. This results in a simple implementation that requires very basic instrumentation - the actuation torques only require pressure sensors measuring the cylinder pressures. This method is favored by commercially available solutions that are marketed as retrofittable systems, where simplicity of implementation is often crucial for commercial viability. This approach is quite sufficient as long as the estimation is performed statically, or when the motion of the manipulator is small enough to have no significant dynamic influence.

For a continuous estimation while the manipulator is in motion, the various parameters describing the dynamic influences need to be accurately identified and/or measured. Some of these are constants, such as the link masses and the inertia tensors. Others are dependent on the operating conditions, for e.g., hydraulic friction, which is dependent on the cylinder velocity, hydraulic fluid temperature etc. The accuracy with which these parameters are identified ultimately decides the accuracy of the consequent estimation of payload. The implementation of this procedure is schematically depicted in the fig. 1.2.

The challenge lies in achieving the optimum trade-off between complexity of the methods implemented for the estimation and the consequent accuracy of results obtained. Existing methods that offer high accuracy usually assume that the input parameters are accurately known, or entail exhaustive estimation procedures to accurately estimate them. This diminishes their practical value, especially if retrofittability is considered to be a requirement. The majority of the existing industry solutions offer simple implementation at the cost of accuracy, or guarantee accuracy only for specific motions of the manipulator, thereby precluding a continuous estimation. This apparent lack of an optimal compromise was used as the motivation for the current

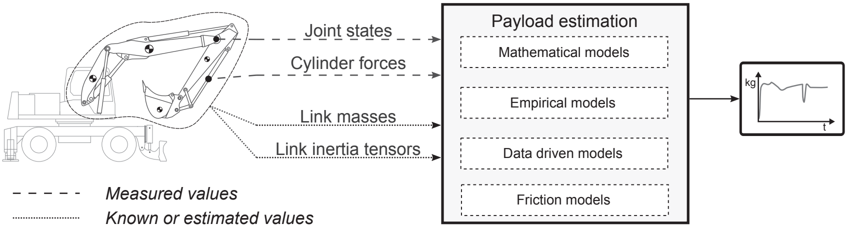

Figure 1.2.: General procedure for payload estimation

work, which deals with developing a self-sufficient method for continuous payload estimation. Self-sufficiency here implies that the aforementioned input parameters for the payload estimation are also identified without the need for proprietary data or exhaustive experiments, without diminishing the obtained accuracy.

To this end, the following work starts with the theoretical background required to understand the problem and its complexities. The key topics discussed in this respect are that of rigid body mechanics, parameter estimation for mechanical manipulators and the modelling of friction effects, since one or all of these themes are repeatedly encountered in developing methods for payload estimation. Subsequently, existing approaches and relevant solutions for payload estimation are surveyed. The chapter closes with a discussion about machine learning approaches and the manner in which they can be applied for this problem. A detailed motivation for the method developed in this work is drawn in the next chapter. The following chapters deal with the description of the concept, its model-based verification and validation through measurements on an actual excavator. The last chapter gives a summary and conclusion of the current work as well as recommendations for further measures.