報告番号	※甲　　第　　号

主　論　文　の　要　旨

論文題目　A Study on Computational Models with Registers and their Application to Software Construction

（レジスタを持つ計算モデルとそのソフトウェア構築への応用に関する研究）

氏　　名　　仙田 涼摩

論 文 内 容 の 要 旨

While most practical programs deal with data values such as ID, timestamp and probability, classical computational models cannot handle data values well. Adding an ability of processing data values to a computational model makes the model Turing equivalent, and many properties become undecidable easily even if only very simple operations to data values are allowed. Register automata (RA) are an extension of finite automata that have a finite number of registers for storing data values from an input word. RA compares the contents of its registers with the current input data value to determine the next transition and is known to have mild powers of processing data values. Register context-free grammars (RCFG), register pushdown automata (RPDA), register tree automata (RTA) and register pushdown systems (RPDS) are extensions of their classical counterparts to handle data values in a restricted way. These models are regarded as models for processing query languages for structured documents such as XML with data values.

The purpose of this dissertation is to build a theoretical foundation for handling programs and databases with data values. To this aim, this dissertation investigates the properties of register models in the following three parts. (1) We investigate these models with respect to the complexities of fundamental decision problems such as membership and emptiness. We further generalize RCFG with reference to guard conditions of production rules. (2) We apply these models to software verification. We show the forward regularity preservation property for RPDS and provide an algorithm for linear temporal logic (LTL) model checking. (3) We investigate realizability problems for the cases that a specification and an implementation are given by a pair of pushdown automaton (PDA) and pushdown transducer (PDT), and a pair of RPDA and register PDT (RPDT). Because the pushdown stack is useful for representing

recursive programs, these problems are important in the field of reactive synthesis of recursive programs.

First, we show the computational complexity of the basic decision problems for RCFG, RPDA, RTA and their subclasses. For example, the membership and emptiness problems for RCFG are EXPTIME-complete, and the membership problem for the ε-rule free RCFG and the growing RCFG is PSPACE-complete and NP-complete, respectively. Furthermore, we define a generalized RCFG (GRCFG) where an arbitrary binary relation is allowed in guards. Although the membership and emptiness problems for GRCFG are undecidable in general, we show that these decidabilities are recovered under two properties of simulation and progress.

Secondly, we show the forward regularity preservation property for RPDS. This property implies the decidability of the forward reachability problem for RPDS. We prove this property by presenting a saturation algorithm that constructs an RA A_{post} such that $L(A_{post}) = post^*_P(L(A))$ from a given RA A and RPDS P, where $post^*_P$ is the forward image of the mapping induced by P. In addition, we propose algorithms for the LTL model checking problem for RPDS with proper labelings of atomic propositions to configurations. These algorithms are useful for a broader range of software verification such as interprocedural data flow analysis and malware detection.

Finally, we investigate the realizability problems for register pushdown models. The realizability problem for a given specification S is to decide whether there exists an implementation satisfying S. Although the problem is important, the problem has not been studied yet when pushdown computational models give specification and implementation. We investigate the realizability problem for the cases that a specification and an implementation are given by a pair of a PDA and a pushdown transducer (PDT), and a pair of an RPDA and a register PDT (RPDT). We show the problem is solvable in EXPTIME if specification and implementation are given by deterministic PDA and PDT, solvable in 2-EXPTIME if they are given by deterministic visibly RPDA and RPDT, and undecidable if the specification is nondeterministic PDA or RPDA. Through this research, we have developed a computational theory for the application of register models. These results can be applied to various fields of software engineering, such as verification and synthesis because these studies allow us to handle recursive programs with data values in a formal way.