

SF2104 拖拉机自主行驶与作业控制方法

吴才聪^{1,2}, 王东旭¹, 陈智博¹, 宋兵兵¹, 杨丽丽¹, 杨卫中^{1*}

(1. 中国农业大学信息与电气工程学院, 北京 100083; 2. 农业农村部农业信息获取技术重点实验室, 北京 100083)

摘要: 针对农业机械无人化作业的应用需求, 该研究基于 SF2104 动力换向线控底盘拖拉机和全球卫星导航系统 (Global Navigation Satellite System, GNSS), 研发了拖拉机自主行驶与作业控制系统。该系统针对田内直线作业与地头转弯, 采用分层控制思想, 将控制系统划分为规划层、控制层和执行层。规划层生成 U 形转弯所需的路网数据, 控制层进行拖拉机横向控制、速度控制、转弯控制、机具升降控制、当前路径更新及终止作业等行为决策; 执行层负责以上行为的配置执行。拖拉机挂载深松机进行深松作业, 并与有人驾驶深松作业进行对照。结果表明, 拖拉机自主行驶与作业控制系统横向偏差的平均标准差为 4 cm, 平均作业速度及其平均标准差分别为 1.66 和 0.09 m/s, 稳定作业时发动机转速的平均标准差为 7.9 r/min, 平均机具位置的极差为 23.8, 均优于有人驾驶。该研究初步实现了拖拉机的自主行驶与作业, 有助于解决农村劳动力紧缺问题。

关键词: 农业机械; 试验; 自动驾驶; 自主作业; 控制系统

doi: 10.11975/j.issn.1002-6819.2020.18.006

中图分类号: S24

文献标志码: A

文章编号: 1002-6819(2020)-18-0042-07

吴才聪, 王东旭, 陈智博, 等. SF2104 拖拉机自主行驶与作业控制方法[J]. 农业工程学报, 2020, 36(18): 42-48. doi: 10.11975/j.issn.1002-6819.2020.18.006 <http://www.tcsae.org>

Wu Caicong, Wang Dongxu, Chen Zhibo, et al. Autonomous driving and operation control method for SF2104 tractors[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2020, 36(18): 42-48. (in Chinese with English abstract) doi: 10.11975/j.issn.1002-6819.2020.18.006 <http://www.tcsae.org>

0 引言

中国农业劳动力数量不断减少, 用工成本日益增长。“一人多机”作业模式可有效减少驾驶员数量, 具有良好的经济效益^[1-4], 而线控底盘和自动驾驶技术为该模式提供了基础支撑^[5-8]。“一人多机”首先要求实现单机的无人驾驶^[9], 但由于感知与避障等技术尚未成熟^[10-12], 研发基于近距离人工遥控的单机自主作业控制方法是当前的重点。在该领域, 国内外学者以无人驾驶与自主作业为目标开展了系列研究, 取得了一定的进展。

Zhang 等^[13-16]基于传统拖拉机, 利用 GNSS (Global Navigation Satellite System)、惯性导航、激光雷达等研发的自动化拖拉机, 可初步实现道路行驶和田内作业的无人操作。凯斯纽荷兰研发的无驾驶室 Magnum 和有驾驶室 NHDrive™ 等无人驾驶概念车辆配备了感应和探测装置, 能够感知并避开障碍物^[17-18]。近年来, 国内有关机构基于 PZ-60 型水稻插秧机^[19-20], 利用工况状态逻辑控制等方法进行行驶机构和插植机构的联合控制, 实现了准无人驾驶作业, 插秧机未配置感知系统, 由操作员监视作业环境和紧急制动; 这种作业模式将单机所需的劳动力从 3 人减至 1 人, 有效节约了用工成本, 在黑龙

江等地得到了应用推广。为减少施药过程中对人的危害, 刘兆朋等^[21]基于 ZP9500 高地隙喷雾机, 利用查询表方法进行直线跟踪、地头转弯和喷雾作业的自动控制, 初步实现了自主喷雾作业。陈黎卿等^[22]基于纯电动型喷雾机, 设计了信息采集与通信系统, 实现了喷雾机的自主行驶与作业控制。李云伍等^[23]基于丘陵山地电动转运车, 基于 GNSS、视觉传感器及毫米波雷达, 实现了转运车的自主行驶。

农机自主作业还需做好地头转弯的路径规划和跟踪, 其核心在于选择转弯模式和平滑转弯路径。Sabelhaus 等^[24-25]基于 Dubins 曲线和 Reeds-Shepp 曲线, 设计了连续曲率掉头路径生成算法, 并分析了 Ω 式、自相交式和鱼尾式转弯的特点及其时间特性。Paraforos 等^[26]为了找出最佳的跳过路径数, 针对历史作业数据, 设计了转弯方式自动判别方法及转弯时间自动分析方法, 通过对 800 hm² 地块连续 4 a 的数据分析, 得出了最佳跳过路径数为 3 条的结论。Yin 等^[27]针对 SPV-6C 插秧机作业路径规划与跟踪控制系统, 基于平滑最小转向圆完成了小幅宽相邻路径地头转弯, 实现了插秧机转弯的自动化。Cariou 等^[28-29]以移动机器人小车为平台, 针对相邻路径掉头问题, 通过基于基本图元的轨迹规划和基于轮胎侧偏角监督估计的模型预测, 优化了掉头时间和掉头区面积。

综上所述, 农机无人驾驶与自主作业的研究尚处于起步阶段。本文拟基于 SF2104 动力换向线控底盘拖拉机和 GNSS, 开发拖拉机自主行驶与作业控制系统, 并通过深松作业验证其性能。

收稿日期: 2020-06-03 修订日期: 2020-08-01

基金项目: 国家重点研发计划项目 (2016YFB0501805)

作者简介: 吴才聪, 博士, 副教授, 博士生导师, 主要从事农机导航与位置服务等研究。Email: wucc@cau.edu.cn

*通信作者: 杨卫中, 博士, 副教授, 主要从事农机导航与位置服务等研究。Email: ywz@cau.edu.cn

1 材料与方方法

1.1 作业机组

拖拉机自主行驶与作业机组的组成如图 1, 主要包括拖拉机、深松机、导航系统、车载控制器和监控终端。



图 1 拖拉机自主行驶与作业机组组成
Fig.1 Composition of autonomous driving and working unit for tractor

拖拉机型号为 SF2104, 后轮驱动, 阿克曼转向, 支持 SAE J1939 协议。轴距为 2 894 mm, 轮距为 1 750 mm, 转弯半径为 7 150 mm, 标定转速为 2 200 r/min, 标定功率为 154 kW。深松机型号为 1SZ-230, 幅宽为 2.5 m, 深松铲数量为 4 铲。导航系统型号为 FARMSTAR F2BD-2.5RD, 包括电动方向盘 (MDU180)、角度传感器 (WAS-3106)、天线控制器一体机 (ZC200) 等。车载控制器型号为 SF9507, 输入/输出通道总计 24 路, 可通过控制局域网 (Controller Area Network, CAN) 控制发动机、变速箱及液压提升系统。监控终端采用手机或电脑, 4G 通信, 可实现拖拉机的远程启停及数据可视化。

1.2 控制系统

1.2.1 系统组成

控制系统的结构见图 2, 包括数据获取单元、规划控制单元及动作执行单元。

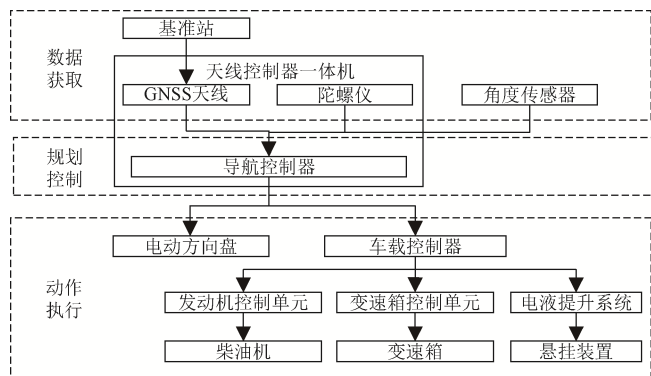


图 2 控制系统结构

Fig.2 Structure of control system

数据获取单元通过 ZC200 内置的 GNSS 天线和陀螺仪获取拖拉机的实时坐标与航向; 通过角度传感器获取

拖拉机前轮(转向轮)的实时角度。GNSS 基准站为 ZC200 播发差分改正数, 实现厘米级定位。

规划控制单元为 ZC200 内置的导航控制器, 是实现导航与控制的核心部件。该单元通过标准串口与电动方向盘进行通信, 通过 CAN 与车载控制器进行通信。

动作执行单元接收控制单元指令并执行相应动作。电动方向盘负责控制前轮转动, 车载控制器通过 CAN 控制发动机转速、变速箱挡位和悬挂装置位置。

1.2.2 导航与控制方法

导航与控制的数据流程图如图 3, 数据来自用户输入和实时获取。导航控制器按分层思想设计, 包括导航规划层、行为控制层和行为执行层。

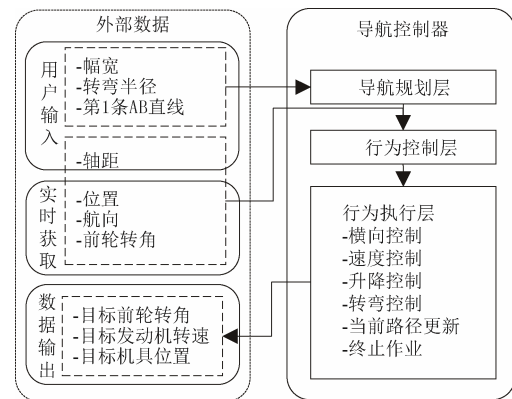


图 3 导航与控制数据流程图

Fig.3 Data flow of navigation and control

导航规划层: 有研究表明^[25], 一般情况下, 单弧转弯时间最短。为此, 本文的路径规划算法采用 FSP (First Turn Skip Pattern)^[30], 该模式将农田划分为多个标准区块和 1 个剩余区块, 可进行单弧转弯及套行作业。该算法通过迭代生成路径编号, 见式 (1)。

$$q_{i,j} = \begin{cases} (2S+1) \cdot (j-1) + 1, & i=1 \\ q_{i-1,j} + S + 1, & \text{mod}(i, 2) = 0 \\ q_{i-1,j} - S, & \text{mod}(i, 2) = 1 \end{cases} \quad (1)$$

式中 $q_{i,j}$ 表示第 j 个区块内的第 i 个序号的路径编号; S 为跳过路径数。

考虑到拖拉机最小转弯半径, 单弧转弯跳过的路径数 S 按式 (2) 计算。

$$S \geq \left\lceil \frac{2R}{W} \right\rceil + 1 \quad (2)$$

式中 W 为作业幅宽, m; R 为最小转弯半径, m。

导航规划的最终输出为路网数据 S_r , 形式如式 (3)。

$$S_r = \{[A_1, B_1], \dots, [A_i, B_i], \dots, [A_n, B_n]\} \quad (3)$$

式中 A_i 、 B_i 为序号为 i 的作业路径的起点和终点坐标 (坐标系为 WGS84), 包含经度和纬度 2 个参数; n 为该区块最后一条作业路径的序号。

为了便于运算, 利用 PROJ API 将该坐标转换为平面形式的 UTM 坐标。可进一步计算任一作业路径距离 A_1B_1 的有向距离 $\overrightarrow{D_1}$, 见式 (4)。

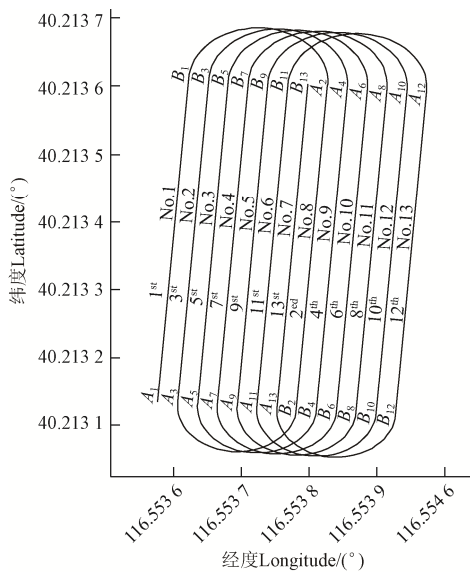
$$\overline{D_i} = d_e \cdot (q_{i,j} - 1) \cdot W \cdot \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \overline{A_i B_i} \\ \overline{A_i B_i} \end{bmatrix} \quad (4)$$

式中 d_e 为相对于 $A_i B_i$ 的延展方向, 向右侧延展时 $d_e=1$, 向左侧延展时 $d_e=-1$ 。

考虑到序号有奇偶之分, A_i 和 B_i 的计算见式 (5)。

$$\begin{cases} A_i = \begin{cases} A_i + \overline{D_i}, & i = 2k-1, k \in N+ \\ B_i + \overline{D_i}, & i = 2k, k \in N+ \end{cases} \\ B_i = \begin{cases} B_i + \overline{D_i}, & i = 2k-1, k \in N+ \\ A_i + \overline{D_i}, & i = 2k, k \in N+ \end{cases} \end{cases} \quad (5)$$

然后, 将生成的 A_i 和 B_i 的 UTM 坐标转换为 WGS84 坐标。经以上步骤, 便可获得最终的导航路径, 即路网数据, 规划结果如图 4。



注: No. q 表示该路径的路径编号为 q , $q=1,2,3, \dots$; i^{th} 表示该路径的作业顺序号为 i , $i=1,2,3, \dots$; A_i 和 B_i 表示作业顺序号为 i 的路径的起点和终点坐标。下同。

Note: No. q indicates that the No. of the path is q , $q=1,2,3, \dots$; i^{th} indicates that the operation sequence No. of the path is i , $i=1,2,3, \dots$; A_i and B_i indicate the start and end coordinates of the path with operation sequence No. i . The same as below.

图 4 路径规划结果

Fig.4 Result of route planning

行为控制层: 行为控制层输入为 S_r 和拖拉机实时位置 P_{now} , 输出为执行层的目标行为, 即 A_{target} , 该行为的分类见表 1。

表 1 目标行为分类

Table 1 Classification of target behaviors

行为类型 Behavior type	行为名称 Behavior name	符号 Symbol
横向控制 Lateral control	AB 直线跟踪	OP
速度控制 Speed control	升速	VU
	降速	VD
升降控制 Lifting control	机具提升	EU
	机具降落	ED
转弯控制 Turning control	地头转弯	TU
当前路径更新 Current path update	当前路径更新	UP
终止作业 Operation ending	终止作业	END

A_{target} 的选择与 P_{now} 有关, 见式 (6)。

$$A_{\text{target}} = \begin{cases} \{\text{OP}\}, & |P_{\text{now}} A_i| \leq |A_i B_i| \\ \{\text{EU, VD}\}, & |P_{\text{now}} A_i| > |A_i B_i| \wedge A_{\text{target}} \neq \{\text{EU, VD}\} \\ \{\text{END}\}, & i = n \\ \{\text{TU}\}, & |P_{\text{now}} A_{i+1}| > \delta \\ \{\text{UP, ED, VU}\}, & |P_{\text{now}} A_{i+1}| \leq \delta \end{cases} \quad (6)$$

式中 δ 为拖拉机实时位置与作业路径起终点间距的判断阈值, 综合考虑定位精度与跟踪精度, 本文取 0.1 m。

行为执行层: 横向控制由农机自动驾驶系统实现, 其算法业已成熟。当 $\text{OP} \in A_{\text{target}}$ 时, AB 直线跟踪行为线程启动, 并向该模块传递 A_{now} 和 B_{now} 的坐标, 该模块将基于轴距 L_{ab} 和拖拉机位置 P_{now} 动态调整目标前轮转角 α , 最终将该值通过标准串口传递给电动方向盘执行。

速度控制通过调节发动机转速 n_{target} 实现, 由车载控制器通过 CAN 传递给发动机。为满足深松作业的农艺和转弯要求, 设置高转速状态 n_{up} 和低转速状态 n_{down} , 分别对应升速与降速行为, n_{target} 满足式 (7)。

$$n_{\text{target}} = \begin{cases} n_{\text{up}}, & \text{VU} \in A_{\text{target}} \\ n_{\text{down}}, & \text{VD} \in A_{\text{target}} \end{cases} \quad (7)$$

机具升降包括机具提升和机具降落, 定义开关量 e_{target} , 满足式 (8), 即当 e_{target} 为 1 时机具提升, 当 e_{target} 为 2 时机具降落。

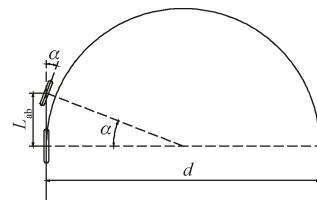
$$e_{\text{target}} = \begin{cases} 1, & \text{EU} \in A_{\text{target}} \\ 2, & \text{ED} \in A_{\text{target}} \end{cases} \quad (8)$$

对于深松作业, 机具降落点 P_{down} 和机具上升点 P_{up} 需要在作业前完成配置, 均由无量纲的机具位置表示, 范围为 $[0, 1\ 000]$, 其中, 0 表示最低位置, 1 000 表示最高位置。导航控制器将以上参数通过 CAN 总线发送至车载控制器, 由车载控制器控制电液提升系统。

地头转弯采用单弧转弯 (图 5), 此时的目标前轮转角 α 为定值。考虑对行与转向要求, α 应满足式 (9)。

$$\alpha = \arctan\left(\frac{2L_{\text{ab}}}{d}\right) \quad (9)$$

式中 L_{ab} 为轴距, m; d 为转弯距离, m。



注: α 为目标前轮转角, ($^{\circ}$); L_{ab} 为轴距, m; d 为转弯距离, m。
Note: α is the target front wheel turning angle, ($^{\circ}$); L_{ab} is the wheelbase, m; d is the turning distance, m.

图 5 转向示意图

Fig.5 Diagram of turning

1.3 试验设计

为验证自主行驶与作业系统的精度与稳定性, 本文设计自动驾驶组和有人驾驶组开展对比试验。试验地块位于北京市顺义区 ($40^{\circ}12'48.32''\text{N}$, $116^{\circ}33'13.43''\text{E}$), 南北长约 90 m, 东西宽约 35 m。

对于自动驾驶组, 将 $R=7.15$ 及 $W=2.5$ 代入式 (2) 可得 S 为 6; 由于地块限制, 设置作业路径数为 10 条,

速度控制和升降控制参数见表 2。有人驾驶组由机手自行操作，实际作业路径数为 11 条。

表 2 速度和升降控制参数
Table 2 Parameters for speed and lifting control

行为名称 Behavior name	参数 Parameters	值 Values
升速 Speed increase	发动机转速 $n_{up}/r.min^{-1}$	1 500
降速 Speed reduction	发动机转速 $n_{down}/r.min^{-1}$	1 000
机具提升 Implement lifting	机具上升点 P_{up}	940
机具下降 Implement lowering	机具降落点 P_{down}	300

2 结果与讨论

2.1 行驶轨迹

自动驾驶和有人驾驶的行驶轨迹如图 6。直观来看，在直线作业段，自动驾驶的行驶轨迹更平直；在地头转弯段，自动驾驶只存在前进轨迹，且轨迹均为 U 形，而有人驾驶存在部分倒车轨迹。

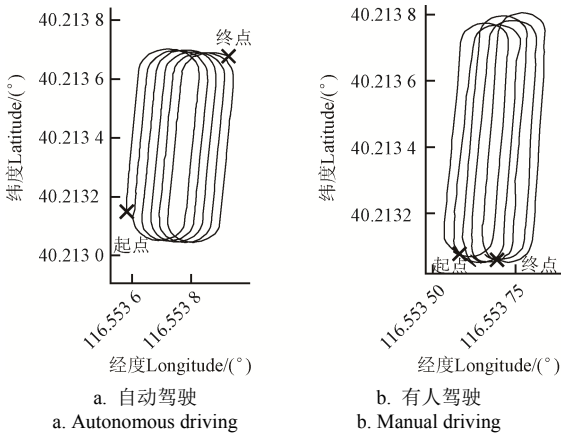


图 6 行驶轨迹对比
Fig.6 Comparison of driving trajectory

2.2 横向偏差

在作业阶段，自动驾驶和有人驾驶的拖拉机横向偏差的平均标准差分别为 4 和 8 cm。其中，图 7 所示为第 1 和第 5 条作业路径的横向控制偏差。显然，自动驾驶的拖拉机横向偏差标准差降低了 50%，作业性能更稳定。

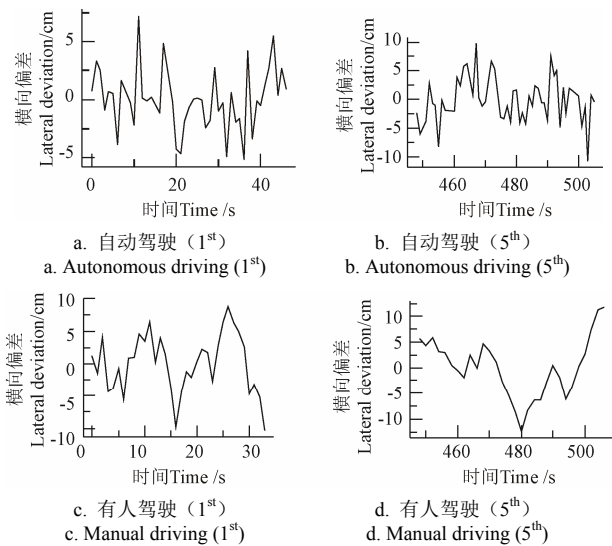


图 7 第 1 和第 5 条作业路径的横向控制偏差
Fig.7 Latereil control devicition of 1th and 5th operation paths

2.3 作业速度

自动驾驶和有人驾驶的平均作业速度分别为 1.66 和 2.98 m/s，平均标准差分别为 0.09 和 0.27 m/s。自动驾驶的控制误差降低了约 67%，表明自动驾驶的作业速度更为平稳（图 8）。

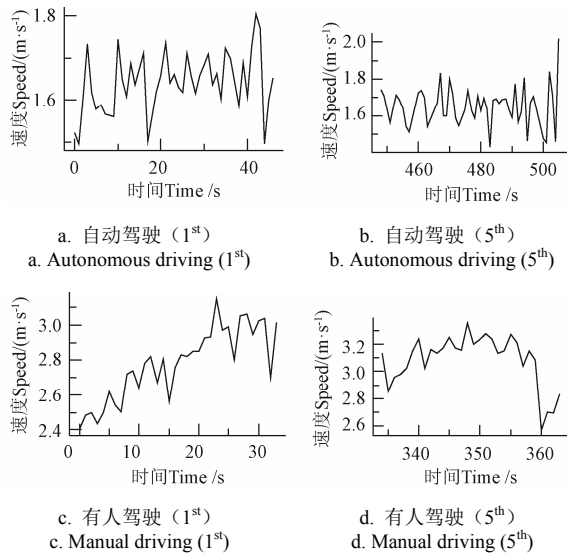


图 8 拖拉机作业速度对比
Fig.8 Comparison of operating speed of tractor

2.4 发动机转速

图 9 为拖拉机的发动机转速对比。自动驾驶的发动机转速有 2 个稳定点，作业阶段稳定在 1 500 r/min 附近，转弯阶段稳定在 1 000 r/min 附近，与设定值一致，仅在直线作业开始或结束时出现超调现象，而有人驾驶的发动机转速没有出现稳定点，自动驾驶在作业阶段（以 130~300 s 为例）和掉头阶段（以 335~425 s 为例）的发动机转速的标准差分别为 7.9 和 9.1 r/min，拖拉机动力控制性能更优。

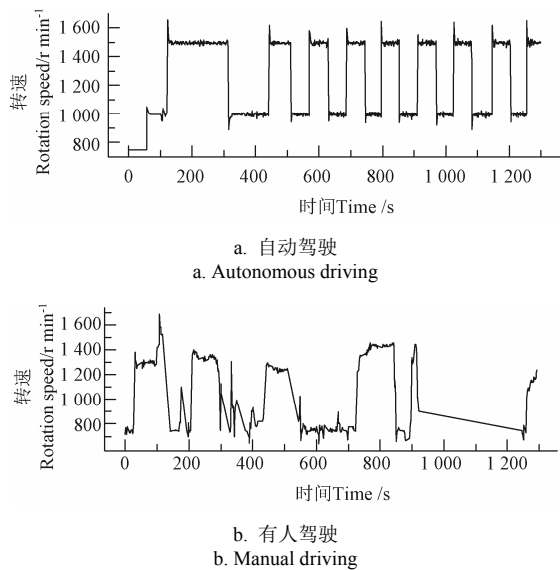


图 9 拖拉机发动机转速对比
Fig.9 Comparison of tractor engine rotation speed

2.5 机具升降

图 10 为机具位置对比。对前 4 个稳定作业阶段（自

自动驾驶: 130~300 s、450~500s、675~725 s、690~740 s;
有人驾驶: 20~130 s、205~300 s、405~535 s、720~
800 s) 的机具升降情况进行分析, 自动驾驶平均机具位
置的极差为 23.8, 有人驾驶平均机具位置的极差为 113.3。
较小的极差反映了自动驾驶的机具升降控制更为精确。

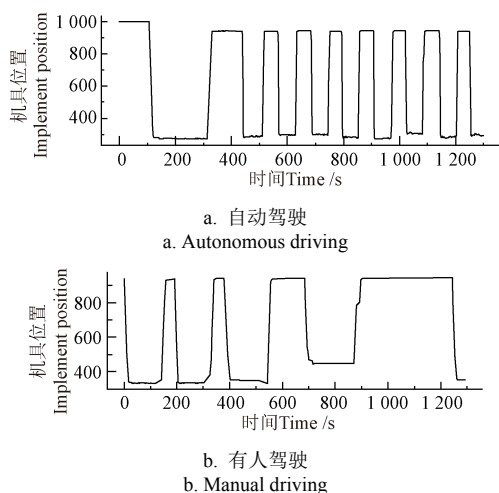


图 10 机具位置对比

Fig.10 Comparison of implement position

3 结 论

1) 基于 SF2104 动力换向拖拉机、GNSS 农机自动导航系统和深松机, 设计了自主行驶与作业控制系统。采用分层控制思想, 将控制系统划分为规划层、控制层和执行层。规划层生成路网数据, 控制层进行横向控制、速度控制、转弯控制和机具升降控制等行为决策, 执行层负责配置执行。

2) 田间对照试验表明, 自动驾驶和有人驾驶的横向偏差的平均标准差分别为 4 和 8 cm, 作业速度的平均标准差分别为 0.09 和 0.27 m/s。自动驾驶稳定作业时发动机转速的平均标准差为 7.9 r/min, 平均机具位置极差 23.8, 均优于有人驾驶作业的对应该指标, 说明自主作业控制技术具有较高的作业精度和稳定性。

[参 考 文 献]

- [1] Lowenberg-DeBoer James, Huang Iona Yuelu, Grigoriadis Vasileios, et al. Economics of robots and automation in field crop production[J]. Precision Agriculture, 2020, 21(2): 278-299.
- [2] Pedersen Søren Marcus, Fountas Spyros, Sørensen Claus G, et al. Robotic seeding: Economic perspectives[M]. Precision Agriculture: Technology and Economic Perspectives. Springer, 2017: 167-179.
- [3] Marinoudi Vasso, Sørensen Claus, Pearson Simon, et al. Robotics and labour in agriculture: A context consideration[J]. Biosystems Engineering, 2019, 184: 111-121.
- [4] Duckett Tom, Pearson Simon, Blackmore Simon, et al. Agricultural robotics: The future of robotic agriculture[EB/OL]. 2018-08-02 <https://arxiv.org/ftp/arxiv/papers/1806/1806.06762.pdf>.
- [5] 韩树丰, 何勇, 方慧. 农机自动导航及无人驾驶车辆的发展综述[J]. 浙江大学学报: 农业与生命科学版, 2018, 44(4): 381-391.
- [6] Han Shufeng, He Yong, Fang Hui. Recent development in automatic guidance and autonomous vehicle for agriculture: A review[J]. Journal of Zhejiang University: Agriculture & Life Sciences, 2018, 44(4): 381-391. (in Chinese with English abstract)
- [7] 董胜, 袁朝辉, 谷超, 等. 基于多学科技术融合的智能农机控制平台研究综述[J]. 农业工程学报, 2017, 33(8): 1-11.
- [8] Dong Sheng, Yuan Chaohui, Gu Chao, et al. Research on intelligent agricultural machinery control platform based on multi-discipline technology integration[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2017, 33(8): 1-11. (in Chinese with English abstract)
- [9] 张漫, 季宇寒, 李世超, 等. 农业机械导航技术研究进展[J]. 农业机械学报, 2020, 51(4): 1-18.
- [10] Zhang Man, Ji Yuhan, Li Shichao, et al. Research progress of agricultural machinery navigation technology[J]. Transactions of Chinese Society for Agricultural Machinery, 2020, 51(4): 1-18. (in Chinese with English abstract)
- [11] Kelc Damijan, Stajanko Denis, Berk Peter, et al. Reduction of environmental pollution by using RTK-navigation in soil cultivation[J]. International Journal of Agricultural and Biological Engineering, 2019, 12(5): 173-178.
- [12] 刘小伟, 吴才聪, 车宇. 无人化农机技术与装备发展趋势[J]. 农机科技推广, 2019(10): 26-27.
- [13] Liu Xiaowei, Wu Caicong, Che Yu. Development trend of unmanned agricultural machinery technology and equipment[J]. Agriculture Machinery Technology Extension, 2019(10): 26-27. (in Chinese with English abstract)
- [14] 何勇, 蒋浩, 方慧, 等. 车辆智能障碍物检测方法及其农业应用研究进展[J]. 农业工程学报, 2018, 34(9): 21-32.
- [15] He Yong, Jiang Hao, Fang Hui, et al. Research progress of intelligent obstacle detection methods of vehicles and their application on agriculture[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2018, 34(9): 21-32. (in Chinese with English abstract)
- [16] 薛金林, 闫嘉, 范博文. 多类农田障碍物卷积神经网络分类识别方法[J]. 农业机械学报, 2018, 49(S1): 35-41.
- [17] Xue Jinlin, Yan Jia, Fan Bowen. Classification and identification method of multiple kinds of farm obstacles based on convolutional neural network[J]. Transactions of Chinese Society for Agricultural Machinery, 2018, 49(S1): 35-41. (in Chinese with English abstract)

- [12] 薛金林, 董淑娴, 范博文. 基于信息融合的农业自主车辆障碍物检测方法[J]. 农业机械学报, 2018, 49(S1): 29-34.
Xue Jinlin, Dong Shuxian, Fan Bowen. Detection of obstacles based on information fusion for autonomous agricultural vehicles[J]. Transactions of Chinese Society for Agricultural Machinery, 2018, 49(S1): 29-34. (in Chinese with English abstract)
- [13] Zhang Chi, Noguchi Noboru, Yang Liangliang. Leader - follower system using two robot tractors to improve work efficiency[J]. Computers and Electronics in Agriculture, 2016, 121: 269-281.
- [14] Zhang Chi, Noguchi Noboru. Development of a multi-robot tractor system for agriculture field work[J]. Computers and Electronics in Agriculture, 2017, 142: 79-90.
- [15] Wang Hao, Noguchi Noboru. Autonomous maneuvers of a robotic tractor for farming[C]// 2016 IEEE/SICE International Symposium on System Integration (SII). Sapporo, Japan: IEEE, 2016. 592-597.
- [16] Wang Hao, Noguchi Noboru. Adaptive turning control for an agricultural robot tractor[J]. International Journal of Agricultural and Biological Engineering, 2018, 11(6): 113-119.
- [17] 关群. 凯斯纽荷兰工业集团推出无人驾驶概念拖拉机[J]. 农业机械, 2016(9): 40-43.
Guan Qun. Case New Holland Industries launches driverless concept tractor[J]. Farm Machinery, 2016(9): 40-43. (in Chinese with English abstract)
- [18] 关群. 凯斯无人驾驶概念拖拉机荣获“最佳设计奖”[J]. 农业机械, 2018(1): 64.
Guan Qun. Case driverless concept tractor won the “Best Design Award”[J]. Farm Machinery, 2018(1): 64. (in Chinese with English abstract)
- [19] 何杰, 朱金光, 罗锡文, 等. 电动方向盘插秧机转向控制系统设计[J]. 农业工程学报, 2019, 35(6): 10-17.
He Jie, Zhu Jinguang, Luo Xiwen, et al. Design of steering control system for rice transplanter equipped with steering wheel-like motor[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2019, 35(6): 10-17. (in Chinese with English abstract)
- [20] 何杰, 朱金光, 张智刚, 等. 水稻插秧机自动作业系统设计与试验[J]. 农业机械学报, 2019, 50(3): 17-24.
He Jie, Zhu Jinguang, Zhang Zhigang, et al. Design and experiment of automatic operation system for rice transplanter[J]. Transactions of Chinese Society for Agricultural Machinery, 2019, 50(3): 17-24. (in Chinese with English abstract)
- [21] 刘兆朋, 张智刚, 罗锡文, 等. 雷沃 ZP9500 高地隙喷雾机的 GNSS 自动导航作业系统设计[J]. 农业工程学报, 2018, 34(1): 15-21.
Liu Zhaopeng, Zhang Zhigang, Luo Xiwen, et al. Design of automatic navigation operation system for Lovol ZP9500 high clearance boom sprayer based on GNSS[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2018, 34(1): 15-21. (in Chinese with English abstract)
- [22] 陈黎卿, 许泽镇, 解彬彬, 等. 无人驾驶喷雾机电控系统设计与试验[J]. 农业机械学报, 2019, 50(1): 122-128.
Chen Liqing, Xu Zezhen, Xie Binbin, et al. Design and test of electronic control system for unmanned drive sprayer[J]. Transactions of Chinese Society for Agricultural Machinery, 2019, 50(1): 122-128. (in Chinese with English abstract)
- [23] 李云伍, 徐俊杰, 王铭枫, 等. 丘陵山区田间道路自主行驶转运车及其视觉导航系统研制[J]. 农业工程学报, 2019, 35(1): 52-61.
Li Yunwu, Xu Junjie, Wang Mingfeng, et al. Development of autonomous driving transfer trolley on field roads and its visual navigation system for hilly areas[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2019, 35(1): 52-61. (in Chinese with English abstract)
- [24] Sabelhaus Dennis, Frank Roben, Lars Peter Meyer zu Helligen, et al. Using continuous-curvature paths to generate feasible headland turn manoeuvres[J]. Biosystems Engineering, 2013, 116(4): 399-409.
- [25] Backman Juha, Piirainen Pyry, Oksanen Timo. Smooth turning path generation for agricultural vehicles in headlands[J]. Biosystems Engineering, 2015, 139: 76-86.
- [26] Paraforos Dimitrios S, Hübner Robert, Griepentrog Hans W. Automatic determination of headland turning from auto-steering position data for minimising the infield non-working time[J]. Computers and Electronics in Agriculture, 2018, 152: 393-400.
- [27] Yin Xiang, Du Juan, Noguchi Noboru, et al. Development of autonomous navigation system for rice transplanter[J]. International Journal of Agricultural and Biological Engineering, 2018, 11(6): 89-94.
- [28] Cariou Christophe, Lenain Roland, Thuilot Benoit, et al. Motion planner and lateral-longitudinal controllers for autonomous maneuvers of a farm vehicle in headland[C]// 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems. St. Louis, MO, USA: IEEE, 2009. 5782-5787
- [29] Cariou Christophe, Lenain Roland, Berducet Michel, et al. Autonomous maneuver of a farm vehicle with a trailed implement: motion planner and lateral-longitudinal controllers[C]// 2010 IEEE International Conference on Robotics and Automation. Anchorage, AK, USA: IEEE, 2010. 3819-3824
- [30] Zhou Kun. Simulation Modelling for In-field Planning of Sequential Machinery Operations in Cropping Systems[D]. Aarhus: Aarhus University, 2015.

Autonomous driving and operation control method for SF2104 tractors

Wu Caicong^{1,2}, Wang Dongxu¹, Chen Zhibo¹, Song Bingbing¹, Yang Lili¹, Yang Weizhong^{1*}

(1. College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China; 2. Key Laboratory of Agricultural Information Acquisition Technology, Ministry of Agriculture and Rural Affairs, Beijing 100083, China)

Abstract: To solve the critical shortage and the increasing cost of rural labor, the concept of “one person, multiple machines” were proposed and an autonomous driving and operating system for SF2104 was developed. The hardware of the system included SF2104 tractor with a power reverser transmission and wire-controlled chassis, WAS-3106 angle sensor, 1SZ-230 subsoiler, GNSS (Global Navigation Satellite System) based auto-steering system for agricultural machinery (FARMSTARF2BD-2.5RD), SF9507 vehicle controller, and mobile monitor such as smartphone and PC (personal computer). The control system mainly included three function units, i.e., data acquisition unit, planning and control unit, and movement unit. The navigation and control method was deployed in the planning and control unit according to the hierarchical control method. The entire method constituted of the layer of navigation planning, the layer of behavior control, and the layer of behavior execution. The operation width, the turning radius and the first operation path (*AB* straight line) from user inputs were transferred to the layer of navigation planning, and it also used to calculate the path network data. The path network data, wheelbase from user inputs and the real-time data (i.e., location, heading and front wheel angle), were transferred to the layer of behavior control involving the target behavior decision. The decision of the target behavior would be transferred to the layer of behavior execution, which derived the target front wheel angle, the target engine rotation speed and the target implement position. The layer of navigation planning generated the path network data to meet the requirement of operating in the field and turning in the headland through the FSP (First Turn Skip Pattern). The layer of behavior control made the decisions of target behavior, including lateral control, speed control, turning control, lifting control, current path update and operation ending. When the tractor entered the operating strip, the system identified the starting point of the operation, and sequentially executed the behavior of implement lowering, the behavior of speed increase, and the behavior of tracking the *AB* straight line. When the tractor finished the operation of the current path, the behaviors of implement lifting, speed reduction, and turning were executed sequentially. The behavior of speed control was executed by controlling the tractor’s engine rotation speed at a high value or a low value through the vehicle controller. The behavior of lifting control was executed by transmitting an implement status value to the controller of the hydraulic lifting system. The behavior of turning control was executed by transmitting a fixed front wheel angle which was calculated by tractor kinematics turning distance. The subsoil operation experiments were carried out in the Shunyi District of Beijing. The experiments included the manual driving group and the autonomous driving group. For the autonomous driving group, the operating trajectories were straight and smooth, the average standard deviation of lateral deviation was 4 cm, the average operating speed was 1.66 m/s, and the standard deviation of operating speed was 0.09 m/s. During the stable operating stage in the field, the standard deviation of engine rotation speed was 7.9 r/min, and the range of the average implement position was 23.8. For the manual driving group, the operating trajectories were not smoother than the trajectories of the autonomous driving group, and the average standard deviation of lateral deviation was 8 cm, the average operating speed was 2.98 m/s, and the standard deviation of operating speed was 0.27 m/s. The stability of engine rotation speed and the range of implement position were also poor in manual driving group. The results showed that the autonomous driving group outperformed the manual driving group in terms of operating accuracy and working stability, which can effectively reduce labor costs. This research provides a platform foundation and theoretical basis for the future research of multi-vehicle and multi-operation collaboration with less human operations.

Keywords: agricultural machinery; experiments; automatic driving; autonomous operation; control system